The macroeconomic dynamics of trade liberalization, resource exploitation, and backstop technologies

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Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

The Macroeconomic Dynamics of Trade Liberalization, Resource Exploitation, and Backstop Technologies

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Proefschrift

ter verkrijging van de graad van doctor aan Tilburg University, op gezag van de rector magnificus, prof. dr. Ph. Eijlander, in het openbaar te verdedigen ten overstaan van een door het college voor promoties aangewezen commissie in de aula van de Universiteit op woensdag 15 mei 2013 om 16.15 uur door

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geboren op 21 juni 1984 te Raamsdonksveer.

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Dankwoord

> *“’k Heb van jou veul schône dinge, hil m’n hart aon oe verpàànd. ’k Zal van jou dus blève zinge: Tilburg schôônste stad van ’t làànd.”*
>
> — uit het Tilburgs Volkslied

Tien jaar Tilburg. Een ontdekkingsreis. Eerst letterlijk, vanuit het Biesboschland met het openbaar vervoer, daarna door openbaringen op velerlei vlakken. Niet in de minste plaats op het gebied van kennisvergaring, de afschrikwekkende waarschuwing van de Prediker ten spijt: “Want in veel wijsheid ligt veel verdriet, en als iemand kennis vermeerdert, vermeerdert hij smart.” De smart en het verdriet lagen echter niet in de kennisvermeerdering, maar in het verlies van meer dan een kennis. In een droevig en voortijdig einde van een veelbelovende samenwerking met mijn promotor Jenny Ligthart. Ik ben en blijf Jenny zeer dankbaar voor alles wat ze voor mij heeft betekend en voor wat ik van haar heb geleerd. Haar aanstekelijke enthousiasme, onuitputtelijke inspiratie, deskundigheid, haar levendige aanwezigheid op de universiteit en daarbuiten, haar oog voor detail, maar ook haar tomeloze inzet die zo belangrijk is geweest voor de totstandkoming van dit proefschrift, zelfs in de laatste zware maanden van haar leven, zal ik nooit vergeten. Haar onuitwisbare invloeden zullen zichtbaar blijven in mijn toekomstige wetenschappelijke werk en verdere leven.

Graag wil ik ook mijn dank betuigen aan Sjak Smulders, omdat hij zich bereid getoond heeft als tweede promotor op te treden en de apotheose van mijn promotietraject in goede banen te leiden. Sjak z’n inzet en inzichten zijn daarenboven van groot belang geweest voor het tweede deel van mijn proefschrift. Een speciaal woord van dank wil ik voorts wijden aan Cees Withagen en Rick van der Ploeg, aan wier project over de economie van klimaatverandering ik thans als postdoctoraal onderzoeker meewerk. Zij hebben mij alle vrijheid en ruimte geboden om me toe te leggen op het onderzoeksgebied binnen hun project dat mij het meest aanspreekt. Bovendien hebben zij veel begrip getoond voor de invloed die de droevige gebeurtenis van Jenny's verlies heeft gehad op de afwikkeling van mijn promotietraject. Cees en Rick dank ik bovendien, benevens Reyer Gerlagh, Ben Heijdra en Aart de Zeeuw, voor het lezen en becommentariëren van mijn manuscript en voor het zitting nemen in de promotiecommissie.

Tien jaar Tilburg. Ik heb veel gelachen en beleefd. Me vaak verbaasd en verwonderd. Daarnaast, om in de woorden van de Prediker te blijven, me ook vaak afgetobt onder de zon en me geoccupeerd met het najagen van wind. Toch waren zelfs laatstgenoemde, van ijdelheid der ijdelheden doordrenkte episodes van het leven als student c.q. promovendus de moeite waard. Voornamelijk dankzij de aanwezigheid van lotgenoten die het gezwoeg op onze onvolprezen, aan de rand van de Oude Warande gesitueerde campus aangenaam maakten. Zonder volledig te willen zijn, hecht ik eraan hier Alexandra, Arian, Jochem, Janus, Kim, Louis, Marta, Martin Knaup, Nathanaël, Pedro, Rob, Salima, Sander, Thomas en Tim met name te noemen. Mijn dank is in het bijzonder groot voor de amusante, al dan niet politiek correcte en relativerende gesprekken met respectievelijk Chris en Patricius, die mij beide voorgingen in hun wetenschappelijke transfers naar de Vrije Universiteit.

Ik heb genoten van alle conversaties met collega's Bas, Henk, Jeffrey, Lex, Martin van Tuijl en vele anderen in gebouw Koopmans, de Cobbenhagen koffiekamer, campuscafé Esplanade, en de mensa. Martin was bovendien altijd bereid mij, als buurman van Jenny, op te vangen wanneer 'JL' nog 'even' in gesprek was, en me te vermaken met allerhande opmerkelijke verhalen over voetbal, economie en overige zaken des levens. Zeer bedankt hiervoor.

Peêr, het was een genoegen om K410 meer dan drie jaar met jou te delen. Hoewel je me steevast als 'huigdrinker' typeerde en we zo nu en dan verwikkeld waren in verbale gevechten over onder meer de 'Ramsey rule' en het lange termijnrendement in een model met heterogene tijdsvoorkeurvoeten—waarbij over en weer hevig gesticulerend, triomfantelijk 'fout!' geschreeuwd werd en de afdrukken van onze hakken nog immer in het zand staan—heb ik je collegialiteit, behulpzaamheid en gezelligheid erg gewaardeerd. Je nuchtere Twentse blik en je eerlijkheid hielpen me zo nu en dan m'n tunnelvisie te doorbreken. Zelfs toen ik me ooit door een overijverige verkoopster in de stad veel te dure wit lederen schoenen aan had laten meten, wist je met een lachsalvo en termen als 'bordeelslippers' te voorkomen dat ik er langer dan een dag mee voor gek heb gelopen. Nog altijd hoop ik dat de vermaarde 'wet van Geer en Peer' ooit het levenslicht zal gaan zien.

Tien jaar Tilburg, waarvan twee jaar trein, maar ook vijf jaar *Huize Cachet* en drie jaar *Ryestreet* met mijn huis- en zaalvoetbalploeggenoten Aki, Bòòt, Eddepet, Hààns, Marijke's, Roeterink, Rwie, Sanders Inc., Stefanovic, en Zjaspère. Ik heb een memorabele tijd met jullie beleefd, die varieerde van gezamenlijk koken, dineren en drinken tot het voeren van nachtelijke gesprekken alsmede het bezoeken van verscheidene biercanti en overige activiteiten in de stad. Het gros van de te aangehaalder plaatse opgedane ervaringen leent zich echter allerminst voor bespreking alhier, maar veeleer voor nabeschouwing elders. Dank voor alle gezamenlijke belevenissen en excuses voor al die keren dat ik als 'Sjaak Afhaak' furore maakte vanwege de beruchte dea*th*lines of andere plichten die mij riepen.

Tijdens tien jaar Tilburg stond het leven in Nieuwendijk en omgeving geenszins stil. Met enige regelmaat was ik dan ook daar te vinden, om op visite te gaan bij deze of gene, te voetballen onder de bezielende leiding van De Heus en Ambtenaar, te 'bloazen' voor Pleuny en Otto, of een bezoek te brengen aan mijn oude stamcafé Marktzicht en de kantine der vv Altena. Mede dankzij Aai, Aart, Capelle, Chenko, Corneque, Elvis, Frietpan, De Graaf, Geer, Gou, Heuvel, Heuvel, Hidde, L.J., Maries, De Portjee, Speedy, Van Velde, Yoer, Yoon, Vendel, Verhoor, Van Zanten en de mede-redactieleden van De Coryfee was dit altijd een groot genoegen. Ook heb ik het altijd erg gewaardeerd wanneer jullie in groten getale, al dan niet aangekondigd, onder aanvoering van Verhoor, te Tilburg kwamen logeren in carnavals- of kermistijd.

Halverwege mijn tijd als promovendus heb ik m'n schoonfamilie in spe, Paul, Wilma, Dorothé, en Niels, leren kennen. Bedankt voor jullie gastvrijheid, de mooie avonden samen waarin alles de revue passeerde, van *dun-dieje-van-dun-dieje* tot politiek-economische beschouwingen, en voor mijn gedenkwaardige ski-debuut dat ik afgelopen winter dankzij jullie heb kunnen maken.

Graag wil ik op deze plaats mijn broertjes Arjan en Remy en mijn ouders Gerrit en Petra bedanken voor alles wat ze voor mij gedaan hebben en doen. Hoewel ik tien jaar geleden verhuisd ben, voel ik me nog altijd erg thuis bij jullie aan de Anemoonstraat, waar ik met veel plezier kom. Ik hoop dat ik ooit wat terug kan doen voor jullie. Ten slotte wil ik Ann bedanken. Ik vind het zeer bijzonder en bewonderenswaardig dat je het aangedurfd hebt om samen met mij naar 020 te verkassen en het leven dat je in Breda opgebouwd had, achter je te laten. Ik ben erg blij met jou en ik weet dat je niet altijd verlegen zit om mijn stichtelijke woorden. Daarom volsta ik met het noemen van de vindplaats 1 Korinthe 13:2, dan kun je ze zelf opzoeken.

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Chapter 1

Introduction

> "*Since the fabric of the universe is most perfect and the work of a most wise Creator, nothing in it takes place without emerging, to some extent, from a maximum or minimum principle.*"
>
> — Leonhard Euler (1708-1783)

In this dissertation, we use dynamic general equilibrium theory to study two different topics in economics. The first part (Chapters 2 and 3) of the dissertation is concerned with the allocation effects and welfare consequences of trade liberalization in small open developing economies. The second part of the dissertation (Chapters 4, 5, and 6) is devoted to the analysis of the energy transition from fossil fuels to backstop technologies in the global economy. Both parts take a macroeconomic general equilibrium perspective, whereas the existing literature is predominated by microeconomic partial equilibrium analyses. Moreover, instead of deriving the allocation of scarce resources that a benevolent, welfare maximizing social planner would advocate, the analysis in both parts of the dissertation focuses on the decentralized market equilibrium in imperfect economies. The remainder of this chapter first introduces the two parts and then sets out the structure of the dissertation.

1.1 Trade Liberalization in Small Developing Economies

One of the ten commandments constituting the notorious 'Washington Consensus' in 1990 is that Latin American countries that were hit by the debt crisis of the 'lost decade' should liberalize their trade in order to promote economic growth, development, and poverty reduction (cf. Williamson, 2000).[1] Subsequently, trade liberalization became a standard conditionality in the structural adjustment programs of the International Monetary Fund (IMF) and the World Bank. As a result, to qualify for getting structural adjustment loans from these Washington-based institutions, developing countries were forced to reduce trade barriers, mainly in the form of cutting their import tariffs and eliminating their quotas (Ebrill, Stotsky, and Gropp, 1999). However, next to serving the purpose of protection of domestic industries, trade taxes in developing countries also constitute an important source of revenue to their governments, which are often highly indebted (cf. Ebrill, Stotsky, and Gropp, 1999; Dalsgaard, 2005; Baunsgaard and Keen, 2010). Figure 1.1 shows tax revenues on international trade as a percentage of total tax revenues for low-income, middle-income, high-income, and OECD countries.[2] The figure shows clearly that governments in the low-income group depend more heavily on trade tax revenue than governments in OECD countries. Taking this extraordinary dependency on trade taxes and the existing fiscal imbalances into account, the IMF and the World Bank repeatedly advocated a coordinated tax-tariff reform that consists of reducing import tariffs, while preventing a decrease in government revenue by simultaneously increasing (or introducing) domestic taxes. In the search for compensatory revenue measures, most emphasis is being placed on the value-added tax (VAT) as a suitable candidate for this purpose (Emran and Stiglitz, 2005). The strategy of reducing trade taxes together with a compensating increase in VAT has already been implemented in a large number of developing countries: between 1990 and 2010, the number of low-income countries with a VAT system increased from 8 to 26 (Baunsgaard and Keen, 2010). Figure 1.2 shows that, during the same period, the collected import tariff rate in low- and middle-income countries exhibited a declining trend.[3]

Despite the intention of the Washington-based institutions, trade liberalization episodes have often not been revenue-neutral for the governments of developing countries. Nearly half of the low-income countries that lowered their collected

[1]The term 'Washington Consensus' was introduced by John Williamson to refer to 'the lowest common denominator of policy advice being addressed by the Washington-based institutions to Latin American countries as of 1989 (Williamson, 2000, p. 251).

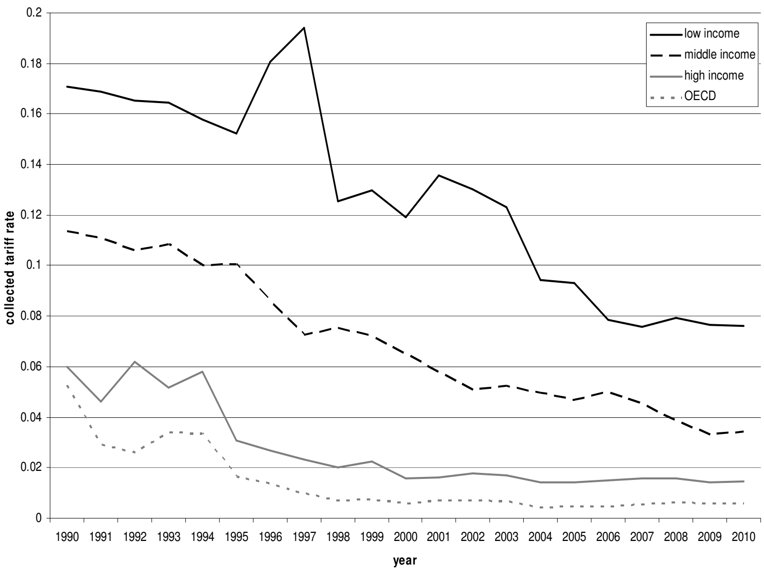
[2]The low-income, middle-income, and high-income country groups are defined by the World Bank classification (World Bank, 2012).

[3]The collected import tariff rate is defined as total import tariff revenue divided by c.i.f. import value (Ebrill, Stotsky, and Gropp, 1999).

Figure 1.1: Taxes on international trade

Notes: The figure shows average tax revenues on international trade (including import duties, export duties, profits of export or import monopolies, exchange profits, and exchange taxes) as a share of total government revenue from 1990-2010 for different country groups, where the low income, middle income, and high income countries are classified according to the World Bank classification. Source: World Bank (2012).

Figure 1.2: Collected import tariff rates



Notes: The figure shows the average collected tariff rate from 1990-2010 for different country groups, where the low income, middle income, and high income countries are classified according to the World Bank classification. Source: World Bank (2012).

tariff rates during the last three decades, have recovered less than 70 percent of the resulting revenue decrease from other sources (Ter-Minassian, 2005). Baunsgaard and Keen (2010) perform a panel data analysis and find that low-income countries on average recover at most 30 cents for each dollar of lost trade tax revenue, even in the long run. For middle-income countries, full recovery is found when only the episodes of falling trade tax revenues are taken into account. Khattry and Rao (2002) argue that structural and institutional constraints underlie the inability of developing countries to recoup revenue loss by employing domestic taxes. The former relates to the large informal sector, mostly in the form of small-scale rural economic activities used for subsistence consumption rather than for commercial production. The latter relates to corruption, political obstacles to expanding domestic tax bases, and the archaic tax administration systems that give rise to a low tax compliance rate.

Although low-income countries were on average not able to recover trade tax revenue losses from other sources, Ter-Minassian (2005) shows that experiences vary widely across them. Besides the countries that suffered from a decrease in total tax revenue, there are also a number that have managed to maintain total revenue more or less unchanged, notwithstanding the decline in trade tax revenue. In order to explain the varying experiences, Ter-Minassian (2005) undertakes a number of case studies from which three important conclusions emerge. First, consumption taxes have played a key role in the countries that managed to recover the trade tax revenue loss. Second, not so much the presence of a VAT, but the design and implementation of the VAT is important.[4] Third, revenue recovery has been strong in countries with IMF programs that explicitly linked trade reform with domestic tax changes.[5]

The theoretical underpinning for the Washington-based policy line of cutting import tariffs and increasing domestic taxes is provided by the welfare gains that these reforms generate in small open economy models. In the seminal papers of Hatzipanayotou, Michael, and Miller (1994) and Keen and Ligthart (2002), a

[4]Design features that have lead to weak VAT systems in, for example, Egypt and Sri Lanka are: excessive exemptions, multiple rates and only partial refunds on capital goods. Conversely, in Senegal the VAT with a single rate and few exemptions worked relatively well (Ter-Minassian, 2005).

[5]Countries that have managed to keep total tax revenues more or less unchanged in spite of declining trade tax revenues are, for example, Pakistan and Uganda. Moreover, some countries even have increased total tax revenues despite a decline in trade tax revenues, like Benin and Malawi (Ter-Minassian, 2005).

coordinated tax-tariff reform of lowering import tariff rates and increasing consumption tax rates in such a way that the consumer price remains unchanged, is shown to unambiguously increase welfare and government revenue. The reason for this promising result is that cutting tariffs improves production efficiency, while the loss in government revenue is more than offset by the one-for-one increase in the consumption tax rate, because the consumption tax base is larger than the tax base of the import tariff. Some other contributions that extend this basic framework in several directions are Haque and Mukherjee (2005), Emran and Stiglitz (2005), Keen and Ligthart (2005), Anderson and Neary (2007), Kreickemeier and Raimondos-Møller (2008), Munk (2008), and Davies and Paz (2011). However, although the existing literature is extensive and growing, it predominantly deploys static (partial) equilibrium frameworks with fixed factor supplies.[6] As a result, the dynamic effects on employment and capital accumulation are being ignored. Especially when the capital intensity differs between the import-competing sector and the rest of the economy, disregarding capital stock dynamics might seriously bias the results. The main driving force of the effects from a change in the import tariff in the dynamic small open economy model of Brock and Turnovsky (1993) is the long-run response of the capital stock, which emphasizes again that ignoring capital stock dynamics may lead to wrong conclusions when studying trade liberalization.

We try to fill this gap in the literature about coordinated tax-tariff reforms by constructing a dynamic general equilibrium model of a small open economy that is populated by forward looking agents who are blessed with perfect foresight, building on the framework of Brock and Turnovsky (1993). In the model of Chapter 2, households derive felicity both from private consumption and leisure, so that labor supply is endogenously determined. Additionally, we deploy a more realistic sectoral structure for a typical developing country by specifying an agricultural export sector and a manufacturing import-competing sector and by assuming that capital goods are not produced domestically, but have to be imported. Physical capital is specific to the export sector and land is specific to the import-competing sector. Conversely, labor is employed in agriculture as well as in manufacturing and is assumed to be perfectly mobile across these production sectors. Moreover, by allowing the households to lend to or borrow from the rest of the world, we

[6] Notable exceptions are Naito 2003; 2006a; 2006b, Portes (2009), and Atolia (2010). The latter two, however, do not provide analytical results and the former three are merely concerned with growth effects in a model with balanced trade.

obtain current account dynamics in response to the tax-tariff reform. Existing studies impose a very stylized tax and tariff system, often with only a consumption tax and an import tariff, which might affect the welfare effect of a reform in a second-best world (Lipsey and Lancaster, 1957). We allow the pre-existing tax and tariff structure to be in line with the situation observed in reality. Accordingly, we assume that the government generates revenue through taxes on consumption goods and proportional taxes on labor income, and through differentiated tariffs on imported consumption goods and capital goods. We use our model to examine the welfare and dynamic allocation effects of an integrated tax-tariff reform that leaves the path of government revenue unaffected.

The reform increases aggregate output in the short run, because of a more efficient allocation of labor over the production sectors and as a result of a rise in employment. In the long run, however, aggregate output and employment decrease, because of a decline in the stock of physical capital. Output and employment in the import-substitution sector fall, whereas output and employment in the export sector rise, more so in the long run than in the short run. We obtain four results concerning welfare and utility effects. First, for a plausible calibration, lifetime utility is shown to increase, implying that the reform moves the economy closer to the second best optimum. The reason is that the reform alleviates the tariff distortion (resulting in too much production and too little consumption of import substitutes, and too much labor supply) more than it exacerbates the distortion of the consumption tax (giving rise to too little labor supply). Intuitively, lower tariff rates not only affect the current allocation of consumption and factors of production between goods and sectors, but also depress capital accumulation in the (at the margin) inefficient import-substitution sector and thus yield a larger welfare gain than in static models with fixed factor supplies. Because of its effect on the development of the wage rate over time, the reform leads to front-loading of labor supply, so that instantaneous utility falls on impact. Therefore, the short-run welfare implications differ from those found in the static literature. Instantaneous utility recovers during the transition period as both consumption and leisure are growing over time. Second, compared to the case of a fixed labor endowment, endogenous labor supply reduces the size of the lifetime welfare gain, the more so the larger the intertemporal elasticity of labor supply. Third, the welfare effect becomes larger if the elasticities of substitution between factors of production in both sectors are higher. Finally, we show that an increase in physical capital mobility amplifies the dynamic component of the welfare effect.

Chapter 3 moves the analysis closer to the reality of developing countries by introducing an informal sector into the model. Schneider and Enste (2000) report informal sector sizes varying from 13 to 76 percent of Gross Domestic Product (GDP) for developing countries. Following Schneider and Enste (2000), the informal sector includes "unreported income from the production of legal goods and services, either from monetary or barter transactions." Throughout the dissertation, we use the terms home production, informal sector, and shadow economy interchangeably. Emran and Stiglitz (2005) have already shown that, in a static model with fixed factor endowments, the welfare gain of a revenue-neutral tax-tariff reform disappears under plausible conditions if allowance is made for the incomplete coverage of VAT owing to the existence of an informal sector. The reason is that the required increase in the VAT rate reinforces the consumption distortion across formal and informal sectors. Their analysis, however, abstracts from the dynamic distortion of the tariff. As established in Chapter 2, in a dynamic setting, import tariffs affect investment by firms in the import-competing sector and thereby the physical capital stock. Given that import-competing sectors are typically much more capital intensive than the rest of the economy, the import tariff is more distorting compared to the consumption tax than it is in a static analysis. Chapter 3 extends the literature by explicitly considering an informal sector and dynamic effects in an integrated framework. Moreover, by introducing overlapping generations in the spirit of Yaari (1965) and Blanchard (1985), the model also features *inter*generational distribution effects. We use the extended model to study the revenue, efficiency, and intergenerational welfare effects of cutting tariffs and increasing destination-based consumption taxes so as to leave domestic consumer price index unchanged.

We find that the reform increases steady-state government revenue, imports, and exports. Employment and output in the informal sector increase, and aggregate formal employment and output go down, more so in the long run than in the short run. Starting from the calibrated equilibrium, however, the reform improves efficiency. The reason is that the reform alleviates the tariff distortion (resulting in too much production and too little consumption of import substitutes) more than it exacerbates the consumption tax distortion (giving rise to excess production in the informal sector). Hence, even when a substantial informal sector exists, the reform gives rise to efficiency gains under plausible conditions, once allowance is made for factor market dynamics. This result is robust with respect to changes in the size of the informal sector within the range observed in reality. The efficiency gain that we find is unequally distributed across generations. Old existing generations benefit more than young and future generations, who may even become worse off if the pre-existing import tariff rate is low or the informal sector is relatively small.

Summarizing, our dynamic analysis of the effects of coordinated tax-tariff reforms contributes to the academic discussion by highlighting an important mechanism that is ignored by the static literature: the welfare costs of import tariffs through their effect on investment and capital accumulation. We show that incorporating this channel leads to larger welfare effects than those obtained in static models. Moreover, we show that, contrary to the results in the static literature with fixed factor supplies, the welfare effect remains positive under plausible parameter values if we acknowledge the existence of a substantial informal sector. Although our analysis shows that the intertemporal welfare effects of tax-tariff reforms should be taken into account, the model that we propose is not meant for providing practical policy advise on governments in developing countries. Several important features of reality are still missing from our study. First, in line with the static literature, our dynamic analysis assumes frictionless labor and capital markets. However, market failures are widespread problems, especially in developing countries (Stiglitz, 1989). The introduction of a market failure that depresses the accumulation of capital in the protected import-substitution sector, for example, might reverse the sign of the efficiency change that we find. Therefore, future research should focus on extending the model to include factor market imperfections. Second, in the current specification of the model, only the import-substitution sector employs physical capital. Introducing an additional export sector that uses capital will lead to an attenuation of the change in the capital stock and other allocation effects and might therefore impact the intergenerational distribution effects of the reform. The change in efficiency is not expected to change qualitatively though. Finally, future work should allow for heterogeneity among households in order to address political economy aspects and *intra*generational distribution effects of the tax-tariff reforms prescribed by the Washington-based institutions.

1.2 Transition from Fossil Fuels to Backstop Technologies

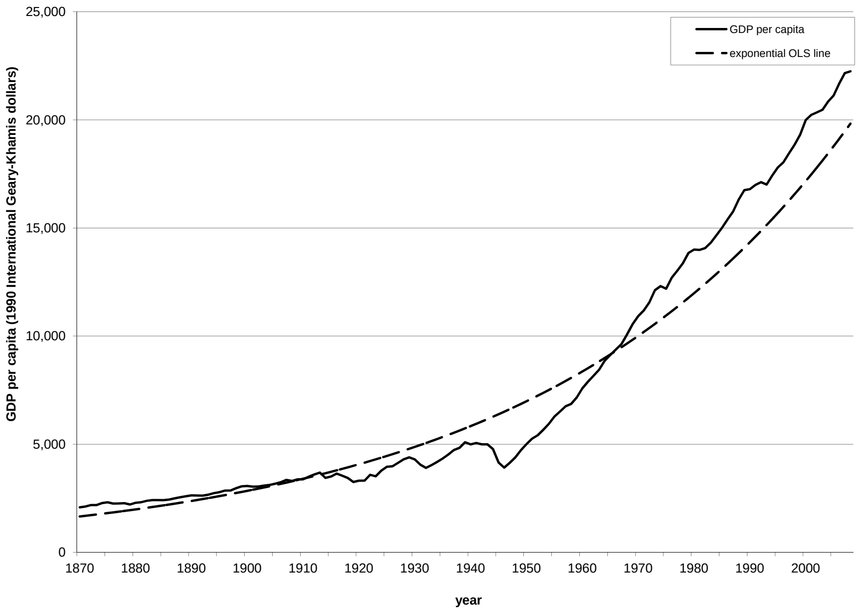
Since the industrial revolution, the world economy is experiencing an unprecedented period of income growth. Figure 1.3 gives an indication of the associated increase in prosperity in industrialized nations, by showing the development of the average real GDP per capita since 1870 in 12 Western European countries. A regression line is added to highlight the exponential growth character of the time path.[7] Much research effort in economics has been devoted to identifying the determinants of income growth and the widely varying growth experiences of different countries. The neoclassical growth model (cf. Ramsey, 1928; Solow, 1956; Cass, 1965; Koopmans, 1965) stressed the role of physical capital accumulation as an engine of growth. However, due to diminishing returns to capital, this growth engine falters in the long run, when the economy approaches its steady-state equilibrium. In the presence of diminishing returns to accumulable factors, sustained growth of income per capita is shown to require a persistent flow of technological progress that continuously augments the productivity of the factors of production. In the neoclassical growth model, this continuous increase in factor productivity enters the economy freely in an exogenous way, like 'manna from heaven'. Subsequent work in the field of growth theory tries to explain the increase in factor productivity endogenously, by introducing spillover effects, learning effects, or by allowing for intentional investment in R&D and education that increase the stock of knowledge (cf. Romer, 1986; Lucas, 1988; Romer, 1990; Aghion and Howitt, 1992; Grossman and Helpman, 1993).

The economic growth theory discussed so far abstracts from the role of non-renewable resources. However, if certain non-renewable resources are necessary for production, the finite availability of those resources has consequences for long-run growth possibilities.[8] To prevent depletion of the resource, resource input needs

[7]The regression line describes $Y = e^{b_0+b_1t}$, where the coefficients b_1 and b_2 are the Ordinary Least Squares (OLS) estimates of the regression specification $\ln Y = b_0 + b_1t + u$, where Y, t, and u denote GDP, time and a disturbance term, respectively.

[8]Following Dasgupta and Heal (1979), a factor of production is called 'necessary' if output would be zero without this factor, i.e. if $Y = F(R, \mathbf{X})$ and $F(0, \mathbf{X}) = 0$, where Y is output, $F(\cdot)$ the production function, R the necessary factor, and the vector $\mathbf{X}$ represents all other factors of production. A necessary exhaustible resource needs to be distinguished from an 'essential' exhaustible resource: an exhaustible resource is essential if, due to its necessity, feasible consumption must necessarily decline to zero in the long run (Dasgupta and Heal, 1979, pp. 197-198).

Figure 1.3: Historical development of GDP per capita



Notes: The figure shows per capita GDP (measured in 1990 International Geary-Khamis dollars) from 1870-2008 in the following 12 West European countries: Austria, Belgium, Denmark, Finland, France, Germany, Italy, The Netherlands, Norway, Sweden, Switzerland and the United Kingdom. Source: Maddison (2008).

to be declining in the long run. Therefore, the importance of non-renewable resources for global energy generation—global energy consumption currently relies for 84 percent on fossil fuels (Energy Information Administration, 2012)—raises the question whether the observed income growth since the industrial revolution is sustainable forever. A clear and negative answer to this question was given in the first report of the 'Club of Rome', named 'Limits to growth' (Meadows et al, 1972). One of the two main conclusions of the report is that "if the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity" (Meadows et al, 1972, p. 29). The subsequent scientific literature points out that the analysis of the Club of Rome ignores two important concepts that may counteract the output effects of declining resource input: substitution and technological change.

By introducing the possibility of substitution of man-made capital inputs for non-renewable resources, the so-called Dasgupta-Heal-Solow-Stiglitz (DHSS) model addresses the first shortcoming of the analysis of the Club of Rome. The DHSS model integrates non-renewable resources into the neoclassical growth framework, and consists of the seminal contributions of Dasgupta and Heal (1974), Solow (1974a; 1974b), and Stiglitz (1974a; 1974b).[9] The main insight from the DHSS model is that, even without technological progress, substitution of capital for non-renewable resources can prevent output from declining in the long run. However, non-declining long-run output can only be obtained under stringent conditions: there should be no constant positive rate of depreciation of capital, the elasticity of substitution between capital and the non-renewable resource is required to be larger than or equal to unity, and the output elasticity of capital should be larger than the output elasticity of the resource. Moreover, even if non-declining long-run output is feasible, it is not necessarily optimal. Consider, for example, a case in which output is produced with capital and a necessary non-renewable resource, the objective is to maximize the net present value of utility, and the pure rate of time preference of the households is constant and positive. Without technological progress, the optimal extraction path of the non-renewable resource does not give rise to a sustainable outcome. The reason is that the ever declining input of the natural resource per unit of capital induces the return to capital and therefore the level of investment to decreases over time.[10] Ultimately, the return to capital will fall below the pure rate of time preference of the households, so that output declines and converges to zero in the long run.

A non-declining long-run output level in the optimum requires ongoing technological progress, which is the second feature of reality that is ignored by the analysis of the Club of Rome. The mere presence of technological progress, however, is not sufficient: if the elasticity of substitution between capital and the resource is smaller than or equal to unity—which is the empirically relevant case (cf. Koetse, de Groot, and Florax, 2008; van der Werf, 2008)—technological progress must have a resource-augmenting component.[11] Moreover, resource-augmenting technical change must be rapid enough to offset the downward pressure on the

[9] Recently, Benchekroun and Withagen (2011) have developed a technique to calculate the closed form solution to the DHSS model.

[10] Implicitly, we have made here the standard assumption that capital and the non-renewable resource are complements in production, in the sense that the second-order cross derivatives of the production function with respect to the factors of production are positive.

[11] Resource-augmenting technical change increases the effective input of energy per physical unit of the resource. It can be interpreted as an increase in the energy efficiency of the resource.

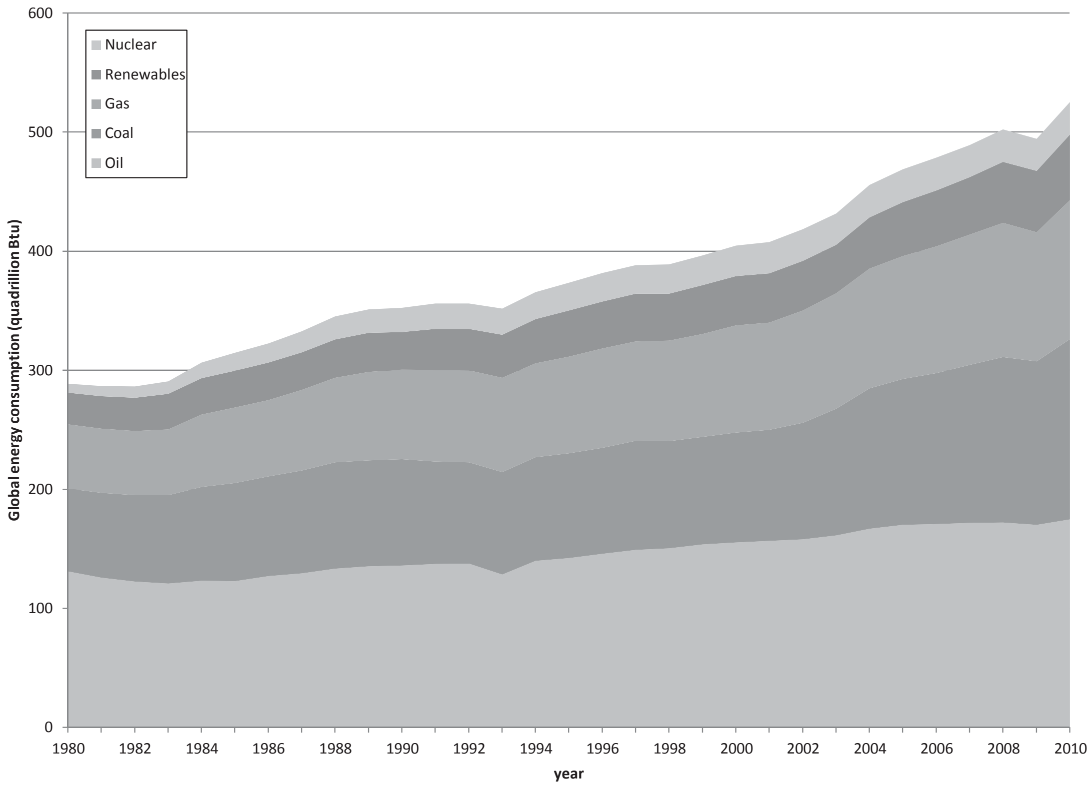
return to capital due to a declining relative resource input over time. To be more specific, the long-run rate of resource-augmenting technical change must be larger than or equal to the rate of time preference. Given these insights from the DHSS model, the sustainability problem boils down to the question whether technical change in reality is expected to be rapid enough and of the right direction to offset the drag that resource dependency imposes on long-run growth.

The DHSS model is unable to answer this question, because it sticks to the exogenous technical change assumption of the neoclassical growth model. Following the endogenous growth literature, more recent work in the field of resource economics abolishes the assumption of exogenous technical progress. Barbier (1999) was the first one to study resource dependence and endogenous technical change in an integrated framework. Scholz and Ziemes (1999) extend his analysis with imperfect competition, and Grimaud and Rougé (2003) analyze growth through creative destruction in a model with a non-renewable resource. Groth and Schou (2002) construct a model in which endogenous growth results from increasing returns to man-made factors. The results of these pioneering studies on non-renewable resources and endogenous growth show that a sustainable outcome is possible if the growth engine has enough power, e.g. if the R&D sector is productive enough. However, by using a Cobb-Douglas specification for the production of final output, technological progress is implicitly assumed to be Hicks neutral, so that the requirement of resource-augmenting technical change is satisfied by construction (cf. Di Maria and Valente, 2008).[12] Recently, Bretschger and Smulders (2012) address this point by taking into account that non-renewable resources and man-made factors are poor substitutes. The direction of technical change in their model, however, is exogenous. The resource-augmenting part of technical change is modeled as a knowledge spillover from the intermediate goods sector. As a result of the assumption of resource-augmenting technical progress, these endogenous growth models might be conceptually biased in the favor of sustainability. Di Maria and Valente (2008) investigate this issue by constructing a growth model with a necessary non-renewable resource in which the direction of technical change is endogenously determined. The main result of their analysis is that technical

[12]Following the terminology of Di Maria and Valente (2008), the assumption of a Cobb-Douglas production function implicitly implies resource-augmenting technical progress, as $Y = AR^{\gamma}K^{1-\gamma} = (A_R R)^{\gamma}K^{1-\gamma}$ with $A_R = A^{\frac{1}{\gamma}}$, where Y, A, A_R, R, and K denote output, Hicks neutral technology, resource-augmenting technology, resource input, and capital, respectively.

change will be purely resource-augmenting in the long run. In line with this outcome, Pittel and Bretschger (2010) find that technical change is biased towards the resource-intensive sector at the balanced growth equilibrium of their model economy in which sectors are heterogenous with respect to the intensity of natural resource use. Therefore, the assumption of a resource-augmenting component in technical change seems to be justified.

Figure 1.4: Global energy consumption



Notes: The figure shows the global yearly consumption of oil, coal, gas, nuclear, and renewable energy from 1980-2010, in British thermal units (Btu). Sources: Energy Information Administration (2012) and International Energy Agency (2012).

Stiglitz (1979) already observed: "For there to be a meaningful natural resource problem, a resource must be in limited supply, must be non-renewable and non-recyclable, necessary, and without perfect substitutes". Hitherto, we have assumed that all those criteria were fulfilled. Although we can indeed safely assume that fossil fuels are non-renewable and non-recyclable on a relevant time scale, the question remains whether they are really necessary and without perfect substitutes. We know from the first law of thermodynamics that energy is a necessary input in production. Energy, however, is not solely derived from coal, gas, and oil. As mentioned before, current global energy generation relies for 84 percent on fossil fuels. The remaining part, however, is derived from alternative energy sources like renewable energy and nuclear energy.[13] Figure 1.4 shows the decomposition of global energy consumption into different energy sources from 1980 until 2010. The ease with which alternative sources of energy can substitute for fossil fuels, to a large extend determines their usefulness and their deployment prospects. The substitutability between fossil fuels and these alternative energy sources depends on technical characteristics. These characteristics are different for each energy source. Therefore, we disaggregate renewable energy into bioenergy, solar energy, geothermal energy, hydropower, ocean energy, and wind energy. Drawing upon the special report about renewable energy sources and climate change mitigation of the Intergovernmental Panel on Climate Change (IPCC, 2012), Intermezzo 1.1 briefly describes the different renewable energy technologies, their application, technical maturity, and output reliability.

Intermezzo 1.1

Bioenergy

Technology	Produces energy from a variety of biomass feedstocks.
Application	Create gaseous, liquid, or solid fuels, or use directly to produce electricity or heat.
Maturity	Varies from ‘R&D phase’ (e.g., liquid biofuel production from algae) to ‘commercially available’ (e.g., ethanol production from sugar).
Reliability	Typically offers constant or controllable output.

Direct solar energy

Technology	Harness the energy of solar irradiance.
Application	Generate electricity, thermal energy, meet direct lighting needs, and (potentially) produce fuels.
Maturity	Varies from ‘R&D phase’ (e.g., fuels produced from solar energy) to ‘mature’ (e.g., solar heating).
Reliability	Variable and, to some degree, unpredictable. Thermal energy storage offers the option to improve output control.

[13] Renewable energy is defined as “any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use” (IPCC, 2012, p. 178).

Geothermal energy

Technology	Utilize the accessible thermal energy from the earth's interior.
Application	Generate electricity or use more directly for applications that require thermal energy.
Maturity	Varies from 'demonstration and pilot phase' (e.g., enhanced geothermal systems) to 'mature' (e.g., hydrothermal power plants).
Reliability	When used to generate electricity, geothermal powerplants typically offer constant output.

Hydropower

Technology	Harnesses the energy of water moving from higher to lower elevations.
Application	Generate electricity.
Maturity	'Mature'.
Reliability	Facilities with reservoirs have a controllable output.

Ocean energy

Technology	Harness the kinetic, thermal, and chemical energy of seawater.
Application	Generate electricity, thermal energy, or produce potable water.
Maturity	'Demonstration and pilot phase'.
Reliability	Varies from variable with differing levels of predictability to controllable operation.

Wind energy

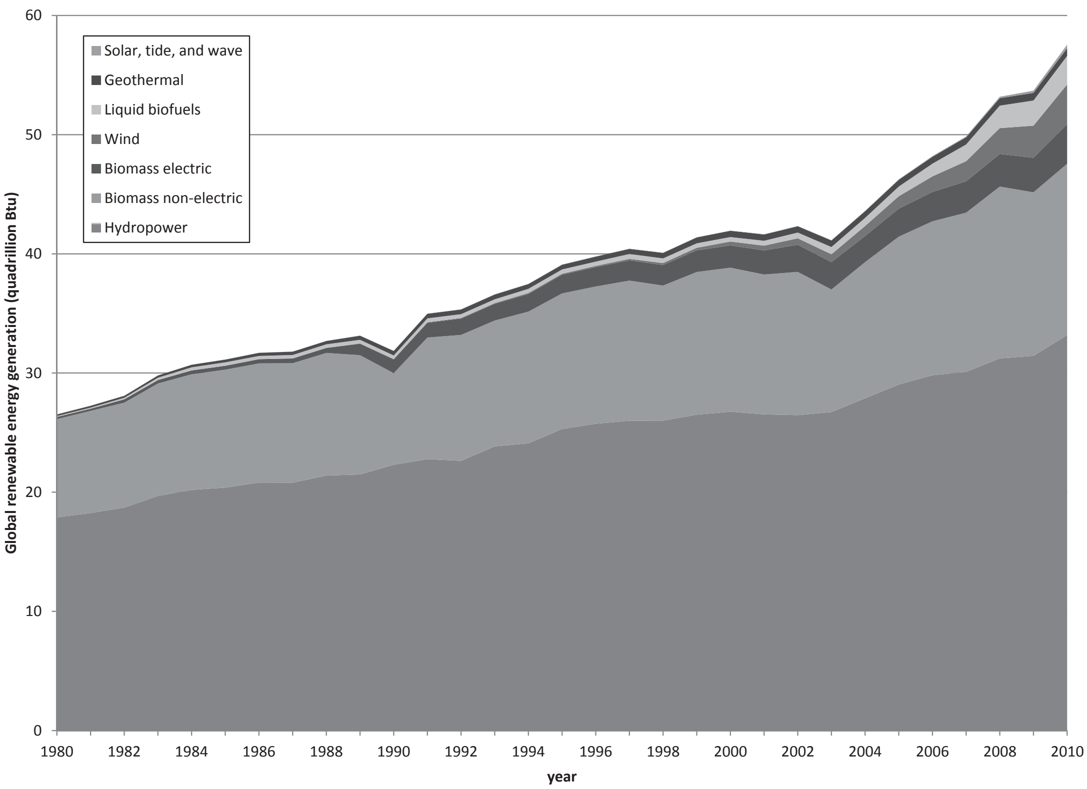
Technology	Harnesses the kinetic energy of moving air.
Application	Generate electricity.
Maturity	Varies from 'R&D phase' (offshore turbines) to 'mature' (onshore turbines).
Reliability	Variable and, to some degree, unpredictable.

Notes: Four gradations of reliability of energy output are distinguished: (i) variable and, to some degree, unpredictable; (ii) variable but predictable; (iii) constant; and (iv) controllable.
Source: IPCC (2012, pp. 8-9).

Figure 1.5 depicts the contribution of each source to global renewable energy generation, from 1980 until 2010. The levelized cost for most renewable energy technologies is currently still higher than the market prices for energy, although renewable energy is already competitive in some cases.[14] Further cost reductions are expected to occur over time, due to additional R&D, economies of scale,

[14] The levelized cost of energy represents the cost of an energy generating system over its lifetime; it is calculated as the per-unit price at which energy must be generated from a specific source over its lifetime to break even. It usually includes all private costs that accrue upstream in the value chain, but does not include the downstream cost of delivery to the final customer; the cost of integration, or external environmental or other costs. Subsidies and tax credits are also not included (IPCC, 2012, pp. 288-291).

Figure 1.5: Global renewable energy generation



Notes: The figure shows the global yearly generation of renewable energy from different sources from 1980-2010, in British thermal units (Btu). Solar and ocean energy are merged in the category 'solar, tide and wave'. Bioenergy is split into liquid biofuels, biomass converted into electricity, and biomass converted into other secondary energy carriers. Sources: Energy Information Administration (2012) and International Energy Agency (2012).

deployment-oriented learning, and increased market competition among renewable energy suppliers (IPCC, 2012, pp. 293-295). Clearly, the levelized cost of a renewable energy technology is not the only determinant of its competitiveness. Other factors like the ability to meet peak electricity demands and the costs of integration in present and future energy systems are important as well. In order to accommodate higher renewable energy shares in the future, energy systems will need to be adapted. Integration of new technologies will require ongoing investments in R&D and capacity building (IPCC, 2012, p. 619). Nevertheless, the share of renewable energy in total energy supply is projected to increase substantially over time, especially in scenarios of ambitious carbon dioxide mitigation. More than half of the scenarios examined in the IPCC report shows a share above 17 percent in 2030 and 27 percent in 2050. The scenarios with the highest renewable energy shares even reach 43 percent in 2030 and 77 percent in 2050 (IPCC, 2012, pp. 791-864).[15]

These figures suggest that renewable sources of energy are, at least on a macroeconomic scale, good substitutes for fossil fuels in the process of energy generation. However, the discussed technologies currently do not provide a *perfect* substitute for fossil fuels. A perfect substitute would capture the whole energy market if its price drops below the current market price of energy. For several (mainly technical) reasons, this is not the case for renewable and nuclear energy. Firstly, the storage of electricity derived from nuclear and renewable sources, for instance, uses much more space than fossil fuels would to carry the same amount of energy, which makes them less suitable for the transport sector (Sinn, 2008; Sinn, 2012, p. 177). Wind and solar power have the additional problem of being less reliable than fossil fuels, because of their intermittent energy supply. This characteristic makes integration of these sources in the energy systems more difficult, particularly when reaching higher shares of these sources in total energy supply. Biofuels, in their turn, are the closest substitutes to fossil fuels. However, they have to be blended with conventional petroleum to avoid technical problems (Hileman, Ortiz, Bartis, Wong, Donohoo, Weiss, and Waitz, 2009, p. 65). Moreover, the supply capacity of bioenergy is limited and its production costs are convex in the level of energy generated (Sinn, 2008; Sinn, 2012, p. 177). It is estimated that satisfying the current global energy demand from the transport sector alone purely with biofuels would already require the total agricultural area available on earth (cf. International Energy Agency, 2006, p. 289). In short, current technologies are at best capable of providing good, but not perfect substitutes for fossil fuels.

The theoretical literature that combines non-renewable resources and endogenous technical change discussed so far, abstracts from the availability and development of good or perfect substitutes for non-renewable resources. Nordhaus (1973, p. 531) was the first one to call a such a substitute for non-renewable resources "with infinite resource base" a 'backstop technology'. The existence of a backstop

[15]The projections of the different scenarios discussed in the IPCC report are based on large scale integrated assessment models. These 'black-box' analyses do not provide insight into the important macroeconomic mechanisms in the energy transition. Moreover, most projections of cost reductions in renewable energy come from the extrapolation of historical learning curves (IPCC, 2012, pp. 190,380,426,483,589,851), instead of resulting endogenously from intentional investments in R&D.

technology fundamentally changes long-run growth perspectives, resource extraction paths, and the effect of non-renewable resource scarcity on investment and the rate and nature of technological progress. It is our aim in this dissertation to identify and explain these effects. Although the DHSS model and more recent contributions in this tradition (cf. Hoel, 1978; Dasgupta and Stiglitz, 1981; Hung and Quyen, 1993; Van der Ploeg and Withagen, 2012) take the existence or the possibility of invention of a backstop technology into account, they assume exogenous technological progress, thereby ignoring the effect of backstop technologies on productivity changes of conventional factors. More recently, Tsur and Zemel (2003) introduced R&D directed at a backstop technology in the analysis. In their model, accumulation of knowledge gradually decreases the per unit cost of the backstop technology. Alternatively, Chakravorty, Leach, and Moreaux (2012) assume that per unit costs of the backstop technology decrease over time through learning by doing. The analyses of Tsur and Zemel (2003) and Chakravorty, Leach, and Moreaux (2012) are both set in a partial equilibrium framework. For our purposes, however, we need a macroeconomic general equilibrium analysis. After all, contrary to the presumption in the partial equilibrium literature that imposes a fixed resource demand function, output growth and biased technological change both affect the demand for the resource, which should be taken into account. There are only a few examples of general equilibrium studies that integrate the necessary tools to study the interactions between the endogenous growth engine, non-renewable resource scarcity, and the existence of a backstop technology.

Tsur and Zemel (2005) construct a general equilibrium model where R&D is able to decrease the unit cost of the backstop technology. However, R&D is only possible in the backstop sector, so that effects on aggregate technological progress cannot be addressed. Tahvonen and Salo (2001) also study the transition between renewable and non-renewable resource in general equilibrium. In their model, however, technological change results from learning-by-doing and does not come from intentional investments (R&D). Moreover, they resort to a Cobb-Douglas specification for final output, thereby ignoring poor substitution between resources and man-made inputs. Finally, Valente (2011) develops a general equilibrium model in which the social planner optimally chooses whether and when to abandon the traditional resource-based technology in favor of the backstop technology. By imposing a Cobb-Douglas production function, prohibiting simultaneous use of the non-renewable resource and the backstop technology, assuming costless endowment of the backstop technology, and solely focusing on the social planner solution, his analysis abstract from real world features that are important for our purposes.

Chapter 4 of this dissertation contributes to the literature by introducing a backstop technology and studying the effects of its availability on the rate of technological progress and the resource extraction path in the decentralized market equilibrium of an analytically tractable, general equilibrium model in which growth is driven by labor allocated to research and development (R&D) directed at the invention of new intermediate goods that are used in the production of final output. We assume knowledge spillovers from the stock of invented intermediate goods to the resource sector and the backstop sector. Energy is necessary for production and is derived from a non-renewable natural resource that can be extracted at zero costs, or generated by a costly backstop technology. In line with the empirical evidence in Koetse, de Groot, and Florax (2008); van der Werf (2008), the elasticity of substitution between energy and man-made factors of production is assumed to be smaller than unity. To show all the relevant mechanisms analytically, we assume that the backstop technology is able to produce a perfect substitute for the non-renewable resource.

The main findings of the analysis in this chapter are, first, that the economy experiences different regimes of energy generation: a resource regime and a backstop regime. Moreover, a regime of simultaneous use may exist, even without imposing the convexities in backstop production or resource extraction costs that are normally required for obtaining this result. Second, the time profile of the rate of technological progress is non-monotonic, whereas it would be monotonically decreasing without the backstop technology available. Third, technological progress is faster during the entire resource regime than it would be without the backstop technology. Finally, the resource extraction path does no longer necessarily have an internal resource extraction peak, usually referred to as 'peak-oil'. Depending on parameter values, it can even be upward sloping until exhaustion. The shape of the resource extraction path depends crucially on the elasticity of substitution between energy and man-made inputs.

Chapter 5 generalizes the model to allow for imperfect substitution between the non-renewable resource and the backstop technology. Accordingly, the elasticity of substitution between the resource and the backstop technology is assumed to be finite, but larger than unity. In this chapter, we obtain the following main results. If the elasticity of substitution between the resource and the backstop technology is large enough, the transition to the backstop technology will take place abrupt and the outcomes of the model are in line with the results obtained Chapter 4. If substitution possibilities are more limited, however, we find a gradual transition from fossil fuels to the backstop technology. The lower the elasticity of substitution between fossil fuels and the backstop technology is, the more prolonged will be the period during which a non-negligible amount of both energy sources is used simultaneously. In line with the literature on the Green Paradox, the availability of a backstop technology leads to more aggressive extraction of the resource in the short run. Using the terminology of Gerlagh (2011), our model thus gives rise to a 'Weak Green Paradox'.[16] At the same time, however, we also find a 'Weak Green Orthodox': an invention that increases the substitutability between the backstop technology and the non-renewable resource leads to a short-run decrease in resource extraction. Finally, we find that the long-run outcomes of the model are not affected by the substitution possibilities in the energy sector as long as the elasticity of substitution exceeds unity.

Chapter 6 generalizes the model of Chapter 4 in another direction: instead of imposing knowledge spillovers to the resource sector, we now assume that R&D can be directed at labor-augmenting or resource-augmenting research. As a result, profit incentives do not only determine the rate, but also the direction of technical change endogenously. In order to obtain clear analytical results, the backstop technology is again assumed to be able to produce a perfect substitute for the non-renewable resource. The main findings of this chapter are as follows. The economy may experience two consecutive regimes of energy generation. Initially, energy generation relies completely on the resource. Depending on the productivity of the available backstop technology, the economy may shift to a regime in which the resource stock is depleted and only the backstop technology will be used to produce energy. In this scenario, short-run resource extraction will be higher than in a model without the backstop technology. The results of this scenario are also relevant for the literature on the 'Green Paradox', because we find that the transition to a backstop technology not only leads to more aggressive resource extraction in the beginning, but also reduces resource-saving technical change compared to an economy without a backstop technology available: the increase in energy efficiency even ceases before the backstop technology becomes competitive. Hence, there are also two consecutive regimes of technical change. Initially, both labor- and resource-augmenting technical change are taking place. Subsequently, a

[16] In the terminology of Gerlagh (2011), a Weak Green Paradox arises if "(the anticipation of) a cheaper clean energy technology increases current emissions".

second regime with purely labor-augmenting technical change commences. Due to the endogeneity of the direction of technical change, the transition to the backstop technology does not take place in all scenarios. If the productivity of the backstop technology is low enough, the economy remains in the resource regime forever: the backstop technology will not become competitive. For intermediate values of the backstop technology productivity, the implementation of the backstop technology is a self-fulfilling prophecy: if investors expect energy generation to rely upon the resource forever, investment in resource-augmenting technical change is attractive so that resource-augmenting technical change is high and the resource indeed remains relatively cheaper than the backstop technology. Conversely, if investors expect the backstop technology to be implemented in the future, resource-augmenting technical change becomes unattractive and eventually drops to zero, so that the backstop technology indeed will become competitive in the future.

Summarizing, the general equilibrium analysis in the Chapters 4, 5, and 6 contributes to the academic literature by providing insight into the transmission mechanisms from the availability of backstop technologies to the R&D and resource extraction sectors of the economy, and into the feedback effect of the R&D sector on the transition from fossil fuels to backstop technologies. The first part of the analysis, Chapter 4, highlights the positive effect of the availability of the backstop technology on labor-augmenting technical change. Moreover, the analysis shows that in general equilibrium, the shift from fossil fuels to a costly backstop technology is accompanied by a sharp increase in investment during the years just before the regime shift, so that part of the resource wealth is transferred to the era in which the resource stock is depleted in order to smooth consumption over time. This increase in investment implies faster technological change during the run-up to the backstop technology. The analysis also shows that part of the resource transfer may take place through an intermediate regime of simultaneous use of the resource and the backstop, if the return to investment becomes lower than the return to resource conservation in a simultaneous use regime. Chapter 5 checks the robustness of this result with respect to the substitutability between the resource and the backstop technology. The magnitude of the increase in investment and hence in technological change at the end of the transition to the backstop technology is shown to depend positively on the elasticity of substitution between the resource and the backstop technology. Simultaneous use of both energy sources now occurs throughout, due to the imperfect substitutability, so that the role of simultaneous use for consumption smoothing becomes obscured.

The final part of the analysis, Chapter 6, allows for both labor- and resource augmenting technical change. The results show that, during the transition from fossil fuels to the backstop technology, the economy will experience only a temporary era of increasing energy efficiency of fossil fuels: after an initial regime of both types of technical change, resource-augmenting technical change drops to zero before the backstop technology is actually implemented, so that the economy is back in the model of Chapters 4 and 5. Moreover, depending on the productivity of the backstop technology, its introduction may become a self-fulfilling prophecy. Regarding resource extraction, the models in Chapters 4, 5, and 6 show that the introduction of the backstop technology leads to front-loading of resource extraction (Weak Green Paradox), and that an increase in the elasticity of substitution between the resource and the backstop technology decreases resource extraction in the short run (Weak Green Orthodox). Finally, the analysis shows that the existence of a backstop technology together with poor substitution between resources and man-made factors may lead to a monotonically increasing resource extraction over time, until the resource stock is depleted.

Although the analysis in the second part of this dissertation advances our understanding of the interaction between backstop technologies, technological progress, and resource extraction, it also has several important limitations that should be stressed at this point. First, because the analysis abstracts from the accumulation of physical capital, consumption smoothing is only possible through resource conservation and investment in innovation. As a result, the increase in innovation during the run-up to the backstop technology that the models with good substitution between the resource and the backstop technology generate, should be interpreted as an increase in investment that coincides with the upper bound on the rise in innovation in a model with multiple assets. Second, the model in its most general form includes two types of technological progress: labor-augmenting and resource-augmenting technological progress. However, there is no separate type of research directed at improving the productivity of the backstop technology. Introducing this possibility will result in additional insights, and is especially important when the model is used for the design of optimal policies in a 'second-best' world. Third, the models in their current form only feature two types of externalities: monopolistic competition in the intermediate goods sector and intertemporal knowledge spillovers. These externalities are standard in endogenous growth models and it is well known that their internalization requires a production subsidy in the intermediate goods sector and subsidies to research and development, respectively. To make the models suitable for the design of optimal environmental policy, two more important elements are missing: stock-dependent extraction costs and feedback effects of pollution from resource combustion on either production or utility. With stock-dependent extraction costs, environmental policy is able to affect the amount of resources that will be left in situ. Feedback effects from pollution are needed to introduce an externality of the combustion of fossil fuels into the model. The first-best optimum then requires, in addition to the mentioned subsidies, a tax on pollution. More interesting, however, are the implications of the environmental externality for the second-best paths of subsidies on different types of research and on the desirability and characteristics of a production subsidy in the backstop sector if the government is not able to impose a tax on pollution. Introducing the necessary ingredients that make the model in this part of the dissertation suitable for sensible environmental policy analysis, is left for future research.

1.3 Structure of the Dissertation

The remaining chapters of this dissertation are based on the following research papers:

Chapter 2:
Ligthart and Van der Meijden (2010): "The Dynamics of Revenue-Neutral Trade Liberalization", mimeo, Tilburg University.

Chapter 3:
Ligthart and Van der Meijden (2010): "Coordinated Tax-Tariff Reforms and the Shadow Economy", mimeo, Tilburg University.

Chapter 4:
Van der Meijden and Smulders (2011): "Resource Extraction, Backstop Technologies, and Endogenous Growth", mimeo, Tilburg University and Vrije Universiteit Amsterdam.

Chapter 5:
Van der Meijden (2012): "Fossil Fuels, Backstop Technologies, and Imperfect Substitution", mimeo, Tilburg University and Vrije Universiteit Amsterdam.

Chapter 6:
Van der Meijden and Smulders (2012): "Backstop Technologies and Directed Technical Change", mimeo, Tilburg University and Vrije Universiteit Amsterdam.

Each chapter contains an introduction, a description of the theoretical model, a discussion of the results, a concluding section, and a mathematical appendix.

Chapter 2

The Dynamics of Revenue-Neutral Trade Liberalization

"Perfection is immutable. But for things imperfect, change is the way to perfect them."

— Owen Feltham (1602-1668)

2.1 Introduction

During the last two decades, the World Bank and the International Monetary Fund (IMF) have strongly advocated trade liberalization programs in developing countries. However, although tax collections on imports in low-income countries have decreased from 5.4 percent of Gross Domestic Product (GDP) in 1985 to 3 percent in 2010, trade taxes continue to be an important source of revenue for governments of developing economies.[1] Between 2000 and 2010, tariff revenue accounted on average for 29 percent of total tax revenue in low-income countries compared to less than 1 percent in OECD countries (World Bank, 2010). Policy advice of Washington-based international financial institutions has stressed the importance of introducing compensating tax measures to recoup the revenue losses from trade liberalization. Much of the discussion has focused on a broad-based consumption tax, such as the value-added tax (VAT), as an alternative source of

[1] We use the World Bank classification of low-income countries, which includes 33 countries in 2011.

revenue. However, very little is known about the intertemporal macroeconomic and welfare consequences of these advocated consumption tax *cum* tariff reforms, an issue that will be taken up in this chapter.

Early theoretical contributions to the literature of piecemeal tariff reform do not pay much attention to the revenue effects of tariff cuts (e.g. Hatta, 1977; and Fukushima, 1979), whereas revenue losses are an important source of distress for governments in developing countries (Baunsgaard and Keen, 2010). More recent studies (e.g., Michael et al., 1993; Hatzipanayotou et al., 1994; Abe, 1995; Keen and Ligthart, 2002; and Kreickemeier and Raimondos-Møller, 2008) acknowledge the government budget constraint and specify conditions under which tax-tariff reforms yield a (static) net efficiency gain. That is, the production efficiency gain induced by the tariff rate cut more than offsets the consumption efficiency loss caused by the increase in the consumption tax rate.[2] So far, little attention has been paid to the potential efficiency gains in a dynamic context. Naito (2006a-b) are notable exceptions. Taking dynamics and forward-looking behavior into account is essential because integrated tax-tariff reforms affect intertemporal relative prices, causing instantaneous utility and allocation effects to differ considerably over time. Moreover, the existing static literature ignores labor market implications and persistently assumes a fixed endowment of production factors. Factor accumulation and the endogeneity of labor supply, however, are features of reality that have an important bearing on the welfare effects of tax-tariff reforms. Naito (2006a-b)—to which our work is related—allow for capital accumulation, but assume exogenous labor supply.[3] Therefore, these studies cannot address the labor market implications of the reform. Moreover, existing studies impose a very stylized tax and tariff system, often with only a consumption tax and an import tariff, which might affect the welfare effect of a reform in a second-best world (Lipsey and Lancaster, 1957). We allow the pre-existing tax and tariff structure to be in line with the situation observed in reality.[4]

This chapter examines the welfare and dynamic allocation effects of an integrated tax-tariff reform that leaves the path of government revenue unaffected.

[2]It becomes less likely to obtain an efficiency gain of coordinated tax-tariff reform when allowance is made for important features of reality such as a hard-to-tax informal sector (Emran and Stiglitz, 2005) and imperfect competition on the goods market (Keen and Ligthart, 2005).

[3]Both papers use quite different modeling frameworks and reform scenarios. Using an endogenous growth model with goods trade, Naito (2006a-b) studies the growth effects of tax-tariff reforms that are revenue neutral only in a present-value sense.

[4]If all taxes would be set at the optimal level instead of based upon reality, production efficiency would be desirable, implying zero tariffs on all goods (Diamond and Mirrlees, 1971).

In so doing, we contribute to the academic literature by incorporating the effects of endogenous labor supply, capital accumulation, and a realistic pre-existing tax system into the analysis. Furthermore, our results are of interest from a policy perspective, as we provide a welfare analysis of a typical reform advocated by the IMF and the World Bank (cf. IMF, 2011). For our analysis, we develop a micro-founded dynamic macroeconomic model of a small open developing economy. We focus on a country that cannot affect world market prices because 67 percent of 33 low-income countries—for which data are available—have an average degree of openness exceeding 50 percent during the 2002–2008 period.[5] Furthermore, the static tax-tariff reform literature has primarily studied small open economies. We solve the model analytically and analyze the main qualitative effects of the tax-tariff reform graphically. To quantify the allocation effects and to get insight into the welfare effects of the reform, we calibrate the model for a typical developing country—using plausible parameters from the data and the literature—and conduct a numerical simulation. We are one of the first to provide quantitative evidence on revenue-neutral tax tariff reforms.[6]

Building on Brock and Turnovsky (1993), our model features two final goods sectors, that is, an agricultural export sector and an import-competing manufacturing sector. Agricultural goods and manufacturing goods are modeled as imperfect substitutes in consumption. Both sectors employ a sector-specific input (i.e., land in the agricultural sector and physical capital in the manufacturing sector) and use intersectorally mobile labor. Forward-looking households supply labor endogenously and are infinitely lived. Our preference specification allows an intertemporal substitution effect on labor supply—via changes in household wealth—which is important for shock propagation (cf. Prescott, 2006, p. 385) and is also found to be of non-negligible size in empirical studies (cf. Kimball and Shapiro, 2008). Finally, the government provides lump-sum transfers to households, which are funded by a mix of pre-existing taxes and import tariffs, based upon the situation in a typical low-income country.[7]

[5] Openness is defined as the sum of exports and imports expressed as a percentage of GDP. The average degree of openness in a sample of 33 low-income countries during 2002-2008 amounted to 66 percent.

[6] The tax-tariff reform literature is primarily theoretical in nature. The regression analysis of Baunsgaard and Keen (2010) and the numerical simulations of Naito (2006a-b) are one of the few quantitative contributions.

[7] We use lump-sum transfers as a shortcut for including government expenditures as a separate argument in the utility function. Because we study a revenue-neutral reform, both approaches are equivalent.

To take into account that changes in the physical capital stock are costly and do not occur instantaneously, we postulate adjustment costs of investment at the level of the firm. Besides leading to more realistic investment dynamics, this feature of our model also allows us to investigate the effect of the degree of capital mobility on our results. Financial capital is assumed to be perfectly mobile, so that the prevailing real interest rate is determined on the world market. The rationale for levying taxes and tariffs in our model is a revenue motive: we assume that the government needs to raise a certain amount of tax and tariff revenue to finance its expenditures. In line with the tax-tariff reform literature, we do not model any frictions and/or imperfections on labor markets and goods markets (e.g., a dual labor market or an informal sector), which are typical of developing countries.[8] In this way, we preclude adding too many deviations from the standard framework at once so that we can isolate the ramifications of relaxing the assumption of a static world with fixed factor endowments. In addition, we keep our model stylized, which allows us to 'inspect the mechanism' behind our comparative dynamic results (cf. Turnovsky, 2011). Our model is small enough to be able to obtain a fair share of the results analytically and to provide a graphical analysis.

We find that the reform increases aggregate output in the short run because of a more efficient allocation of labor over the production sectors and as a result of a rise of employment. The increase in employment occurs because households increase their labor supply in response to the foreseen fall in their human capital. In the long run, however, aggregate output and employment decrease, because of a decline in the stock of physical capital. Output and employment in the import-substitution sector fall, whereas output and employment in the export sector rise, more so in the long run than in the short run. The gross volume of trade (so-called market access) falls in the short run, but increases in the long run. Concerning welfare and utility, we obtain four results. First, for a plausible calibration, lifetime utility is shown to increase, implying that the reform moves the economy closer to the second best optimum. The reason is that the reform alleviates the tariff distortion (resulting in too much production and too little consumption of import substitutes, and too much labor supply) more than it exacerbates the distortion of the consumption tax (giving rise to too little labor supply). Because of the rise in labor supply, instantaneous utility falls on impact, causing the short-run welfare

[8]Notable exceptions are Haque and Mukherjee (2005) and Keen and Ligthart (2005), who analyze the implications of firms' market power on goods markets, and Emran and Stiglitz (2005), who model an informal sector.

implications to differ from those found in the static literature. Instantaneous utility recovers during the transition period as both consumption and leisure are growing over time. Second, compared to the case of a fixed labor endowment, endogenous labor supply reduces the size of the lifetime welfare increase, the more so the larger the intertemporal elasticity of labor supply. Third, in terms of welfare losses, the harmfulness of the tariff rate on imported consumption goods increases with the size of the substitution elasticities between factors of production in both sectors. Finally, we disentangle the static and dynamic part of the welfare effect and show that an increase in capital mobility amplifies the dynamic welfare effect.

The remainder of the chapter is structured as follows. Section 2.2 sets out the model for a small open developing country. Section 2.3 solves the model analytically and Section 2.4 summarizes the model graphically. Section 2.5 studies the macroeconomic dynamics and the welfare effects of tax-tariff reform for a plausible calibration of the model. Finally, Section 2.6 concludes the chapter.

2.2 The Model

This section describes our dynamic macroeconomic model for a typical small open developing economy. The modeling framework allows endogenous labor supply and physical capital accumulation and thereby goes beyond the basic tax-tariff reform framework based on fixed factor endowments.[9] Subsequently, we discuss household, firm, and government behavior.

2.2.1 Households

The infinitely-lived representative household, which is endowed with perfect foresight, allocates one unit of its time in each period between working and leisure. Instantaneous utility is derived from private consumption and leisure according to a logarithmic specification. Lifetime utility as of time t is given by

$$\Lambda(t) \equiv \int_t^{\infty} \left[\varepsilon \ln C(z) + (1-\varepsilon)\ln(1-L(z))\right] e^{-\rho(z-t)} dz, \quad 0 < \varepsilon < 1, \tag{2.1}$$

where $C(z)$ and $L(z)$ denote 'composite' consumption and labor supply in period z, respectively, ρ represents the pure rate of time preference, and ε is the utility weight of private consumption. Equation (2.1) allows a wealth effect on labor

[9] Compared to the static tax-tariff reform literature, our consumption side is simplified by focusing on two consumption goods rather than many.

supply, which is common in business cycle models (cf. King et al., 1988) and dynamic macro models more generally (cf. Heijdra, 1998).[10] Following Backus et al. (1994), the index of composite consumption is described by a constant elasticity of substitution (CES) specification

$$C(z) = \left[\gamma C_M(z)^{\frac{\sigma_C - 1}{\sigma_C}} + (1-\gamma) C_E(z)^{\frac{\sigma_C - 1}{\sigma_C}}\right]^{\frac{\sigma_C}{\sigma_C - 1}}, \tag{2.2}$$

where $C_M(z)$ and $C_E(z)$ are consumption of the manufacturing good and the agricultural good, respectively, $0 < \sigma_C \ll \infty$ is the elasticity of substitution between the two commodities, and $0 < \gamma < 1$ determines their relative weight. By choosing a CES sub-utility function, we are able to explore the empirically relevant case of σ_C smaller than unity (Dennis and Iscan, 2007). The flow budget constraint of the household is:

$$\dot{A}(z) = rA(z) + (1 - t_L)w(z) + T(z) - X(z), \tag{2.3}$$

where r is the world market real rate of interest, $A(z)$ denotes financial wealth, t_L is an exogenously given tax on labor income, $w(z)$ is the real wage rate, $T(z) > 0$ are lump-sum government transfers, $X(z)$ is 'full' consumption, and a dot above a variable indicates a time derivative (e.g., $\dot{Y}(z) \equiv dY/dz$). We define full consumption as the sum of total expenditure on consumption and the opportunity costs of leisure

$$X(z) \equiv p(z)C(z) + w(z)(1 - t_L)[1 - L(z)], \tag{2.4}$$

where $p(z)$ is the 'ideal' price-index of composite consumption

$$p(z) = \Omega_p \left[\gamma \left[(1-\gamma)p_M(z)\right]^{1-\sigma_C} + (1-\gamma)\left[\gamma p_E(z)\right]^{1-\sigma_C}\right]^{\frac{1}{1-\sigma_C}},$$

with $\Omega_p \equiv [\gamma(1-\gamma)]^{-1} > 0$ and $p_M(z)$ and $p_E(z)$ denoting the domestic consumer prices of the manufacturing and the agricultural good. The world market prices of both consumption goods are exogenously given and normalized to unity. We choose the exported agricultural good as the numeraire. The domestic consumer prices are then a function of the government's tax instruments only

$$p_M(z) = (1 + t_C(z))(1 + \tau_M(z)), \quad p_E(z) = 1 + t_C(z), \tag{2.5}$$

[10] Some business cycle studies, however, use Greenwood et al. (1988) preferences in which case the wealth effect on labor supply is eliminated.

where $\tau_M(z)$ is an *ad valorem* import tariff on the imported good and $t_C(z)$ is a destination-based (*ad valorem*) consumption tax, which is levied upon the tariff-inclusive import price. In line with IMF policy advice (cf. IMF, 2011) and a fair share (53 percent) of existing VAT systems (cf. Ebrill et al., 2001), a single tax rate applies to both consumption goods. Having only a single rate of VAT considerably reduces both tax compliance and administration costs, which is important for developing countries with typically weak administrative capacities (cf. Munk, 2008).[11]

Because of the time-separable specification of the lifetime utility function, the optimization problem of the household can be solved in two stages. In the first stage, the representative household chooses time paths for $C(z)$ and $L(z)$ to maximize lifetime utility (2.1) subject to its flow budget constraint (2.3). In the second stage, composite consumption is divided between consumption of the two commodities. The first stage of the optimization problem gives rise to the following two optimality conditions:

$$\frac{1-\varepsilon}{\varepsilon}\frac{C(z)}{1-L(z)} = \frac{(1-t_L)w(z)}{p(z)}, \tag{2.6a}$$

$$\frac{\dot{X}(z)}{X(z)} = \frac{\dot{C}(z)}{C(z)} + \frac{\dot{p}(z)}{p(z)} = r - \rho, \tag{2.6b}$$

$$\lim_{z\to\infty} A(z)e^{-r(z-t)} = 0. \tag{2.6c}$$

Equation (2.6a) sets the marginal rate of substitution between consumption and leisure equal to the relative price of the two. Equation (2.6b) is a standard Euler equation showing that full consumption growth is proportional to the difference between the real rate of interest and the pure rate of time preference. Equation (2.6c) is the No-Ponzi-Game solvency condition. The first equality in (2.6b) uses (2.4) and (2.6a), which together imply that expenditures on composite consumption and on leisure are fixed fractions of full consumption:

$$p(z)C(z) = \varepsilon X(z), \quad (1-t_L)w(z)[1-L(z)] = (1-\varepsilon)X(z). \tag{2.7}$$

Because of the small open economy assumption, the real interest rate is exogenously given and fixed, so that the condition $r = \rho$ needs to be imposed for a

[11]By employing a single consumption tax rate we deviate from the static tax-tariff reform literature, which assumes that changes in different tariff rates on different goods are compensated by changes in differential tax rates on consumption goods. Obviously, the latter specification is of much less practical value.

steady state to exist. Intuitively, the economy would keep accumulating assets—and cease being small in world capital markets—if $r > \rho$ or be depleting assets if $r < \rho$. It follows from the Euler equation that the time profile of full consumption is flat. By integrating (2.3) and using $r = \rho$, we find that full consumption is a constant fraction of total wealth,

$$X(z) = \rho \left[A(z) + H(z)\right], \tag{2.8}$$

where $H(z)$ denotes human capital, which is defined as the after-tax present discounted value of the household's time endowment:

$$H(t) \equiv \int_t^{\infty} \left[(1 - t_L)w(z) + T(z)\right] e^{-r(z-t)} dz. \tag{2.9}$$

The second stage of the household's optimization problem yields demand functions for manufacturing goods and agricultural goods:

$$C_M(z) = \gamma^{\sigma_C} \left(\frac{p_M(z)}{p(z)}\right)^{-\sigma_C} C(z), \quad C_E(z) = (1-\gamma)^{\sigma_C} \left(\frac{p_E(z)}{p(z)}\right)^{-\sigma_C} C(z).$$

Commodity demand depends on relative goods prices, the elasticity of substitution between manufacturing goods and agricultural goods, aggregate consumption, and the preference weight given to each commodity.

2.2.2 Firms

We consider a production structure roughly resembling that of a typical developing economy, consisting of an agricultural export sector and a manufacturing import-substitution sector. There are three factors of production, that is, labor, land, and physical capital.[12] Both sectors deploy labor—which is perfectly mobile across sectors—and a sector-specific factor. Land is specific to the export sector and physical capital is specific to the import-substitution sector. Capital goods are imported and are not being produced domestically.

Firms in the import-substitution sector produce the manufactured good according to an CES production function:

$$Y_M(z) = \Omega_M \left[\alpha_M K(z)^{\frac{\sigma_M - 1}{\sigma_M}} + (1-\alpha_M) L_M(z)^{\frac{\sigma_M - 1}{\sigma_M}}\right]^{\frac{\sigma_M}{\sigma_M - 1}}, \quad 0 < \sigma_M \ll \infty, \tag{2.10}$$

[12] Imported intermediate goods play an important role in developing countries. Although we do not formally model intermediate inputs, capital can be thought of being defined in a broad sense, including intermediates.

where $\Omega_M > 0$ is a productivity index, $K(z)$ represents physical capital, $L_M(z)$ is employment in the import-substitution sector, σ_M denotes the elasticity of substitution between physical capital and labor, and $0 < \alpha_M < 1$ determines the importance of physical capital in production. By choosing a CES specification of the production function we are able to impose an elasticity of substitution below unity, in accordance with the empirical evidence in Chirinko (2008). We normalize the world market price of imported capital goods to unity, so that the domestic producer price for capital goods equals

$$p_I(z) = 1 + \tau_I, \tag{2.11}$$

where τ_I denotes an exogenously given *ad valorem* import tariff on capital goods. Following Uzawa (1969), the firm faces a strictly concave accumulation function:

$$\dot{K}(z) = \left[\Psi\left(\frac{I(z)}{K(z)}\right) - \delta\right] K(z), \qquad \Psi(0) = 0, \quad \Psi'(\cdot) > 0, \quad \Psi''(\cdot) < 0, \tag{2.12}$$

where $\Psi(\cdot)$ denotes the installation cost function, $\delta > 0$ is the constant rate of capital depreciation, and $I(t)$ denotes gross investment. The degree of physical capital immobility is given by $\chi_K \equiv -(I/K)\Psi''/\Psi' > 0$ and , where a small χ_K characterizes a high degree of capital mobility. Note that the limiting cases of $\chi_K \to 0$ and $\chi_K \to \infty$ correspond to perfect and no capital mobility, respectively. The firm chooses time profiles for employment and investment to maximize the discounted value of its cash flows:

$$V_K(t) \equiv \int_t^\infty \left[(1 + \tau_M(z))Y_M(z) - w(z)L_M(z) - (1 + \tau_I)I(z)\right] e^{-r(z-t)} dz, \tag{2.13}$$

subject to the production function (2.10) and the accumulation equation (2.12). The firm takes the real wage rate and the initial stock of physical capital as given. The conditions characterizing the optimum are:

$$w(z) = [1 + \tau_M(z)][1 - \theta_K(z)]\frac{Y_M(z)}{L_M(z)}, \tag{2.14a}$$

$$1 + \tau_I = q(z)\Psi'\left(\frac{I(z)}{K(z)}\right), \tag{2.14b}$$

$$\frac{\dot{q}(z) + [1 + \tau_M(z)]\theta_K(z)\frac{Y_M(z)}{K(z)}}{q(z)} = r + \delta - \left[\Psi\left(\frac{I(z)}{K(z)}\right) - \Psi'\left(\frac{I(z)}{K(z)}\right)\frac{I(z)}{K(z)}\right], \tag{2.14c}$$

$$\lim_{z\to\infty} q(z)K(z)e^{-r(z-t)} = 0, \tag{2.14d}$$

where $\theta_K(z)$ is the output elasticity of physical capital and $q(z)$ denotes Tobin's q, which measures the market value of physical capital relative to its replacement costs. Condition (2.14a) set the real wage rate equal to the marginal product of labor. By equating marginal cost and marginal revenue of investment, (2.14b) gives investment demand. The evolution of Tobin's q over time is determined by equation (2.14c), which equates the return on physical capital—consisting of the sum of the change in Tobin's q and the marginal product of capital—with the user cost of physical capital.[13] Equation (2.14d) is the transversality condition for the firm's optimization problem.

Firms in the export sector produce the agricultural good according to:

$$Y_E(z) = \Omega_E \left[\alpha_E Z^{\frac{\sigma_E - 1}{\sigma_E}} + (1-\alpha_E) L_E(z)^{\frac{\sigma_E - 1}{\sigma_E}} \right]^{\frac{\sigma_E}{\sigma_E - 1}}, \quad 0 < \sigma_E \ll \infty, \qquad (2.15)$$

where $\Omega_E > 0$ is a productivity index, Z represents the fixed factor land, $L_E(z)$ is employment in the export sector, σ_E denotes the substitution elasticity between land and labor, and $0 < \alpha_E < 1$ determines the importance of land in production. The CES specification of the production function enables us to examine the empirical relevant case in which the substitution elasticity between land and labor is smaller than unity (cf. Salhofer, 2000). Profit maximization gives rise to the following two first-order conditions:

$$\begin{aligned} w(z) &= [1 - \theta_Z(z)] \frac{Y_E(z)}{L_E(z)}, \\ r_Z(z) &= \theta_Z(z) \frac{Y_E(z)}{Z}, \end{aligned}$$

where $\theta_Z(z)$ is the output elasticity of land and $r_Z(s)$ denotes the rental rate on land. The government is not able to tax rents on land, because of the lack of clear property titles, which is a widespread problem in developing countries (cf. De Soto, 2001).

2.2.3 Government

The government's objective is to raise an exogenously given amount of revenue at each instant of time, which is employed to provide lump-sum transfers to households. Because of a lack of lump-sum taxes and land rental taxes, the government

[13] Without adjustment costs, we have $\Psi(\cdot) = I(z)/K(z)$, which yields $\chi_K = 0$. Equation (2.14b) then reduces to $q(z) = 1 + \tau_I$. In this case, $q(z)$ and $K(z)$ adjust instantaneously to their steady-state levels. Consequently, equation (2.14c) collapses to $\frac{1+\tau_M(z)}{1+\tau_I} \frac{\partial Y_M(z)}{\partial K(z)} = r + \delta$, which is the familiar rental rate derived in a static framework.

finances its spending by the following menu of distortionary taxes: tariffs on imported final consumption and investment goods, taxes on domestic consumption, and taxes on labor income.[14] We abstract from the corporate income tax in view of its small revenue share in developing countries. For simplicity, and following most of the literature, we assume a hundred percent compliance rate for all taxes.[15] Then, the budget identity of the government is given by:

$$\begin{aligned} T(z) = {} & t_C(z)\left[C_E(z) + (1+\tau_M(z))C_M(z)\right] + t_L w(z)L(z) \\ & + \tau_M(z)\left[C_M(z) - Y_M(z)\right] + \tau_I I(z). \end{aligned} \tag{2.16}$$

The first term on the right-hand side represents consumption tax revenue and the second term captures revenue generated by the labor income tax. The third and fourth term denote revenue from the tariffs on the imported consumption good and the capital good, respectively.

2.2.4 Foreign Sector

The relative world market prices are chosen such that our small open model economy imports part of the manufacturing goods that are being consumed domestically and exports part of the domestically produced agricultural goods. Because capital goods are not produced domestically, aggregate imports are given by $IM(z) = C_M(z) - Y_M(z) + I(z)$. Exports are equal to the difference between domestic production and consumption of the agricultural good: $EX(z) = Y_E(z) - C_E(z)$. Accordingly, the trade balance is given by

$$TB(z) = Y_E(z) + Y_M(z) - C_E(z) - C_M(z) - I(z). \tag{2.17}$$

The current account of the balance of payments is equal to income from net foreign assets plus the trade balance: $\dot{F}(z) = rF(z) + TB(z)$, where $F(z)$ denotes the stock

[14] Since there are no externalities associated with the production of the manufactured good, tariffs are not motivated by an infant industry argument, but are only employed by the government to raise revenue.

[15] Most developing countries are better at collecting import duties than consumption taxes. One may then argue that switching from a tax with high compliance to one with low compliance may require a higher consumption tax rate to maintain revenue neutrality. However, 55 percent of gross VAT revenue is collected at the border (Ebrill et al. 2001), which alleviates the effect of the compliance cost differential. See Turnovsky and Basher (2009) for an analysis of tax enforcement in a two-sector developing country.

of net foreign assets. The intertemporal budget constraint for the economy is given by:

$$F(t) = -\int_t^\infty TB(z)e^{-r(z-t)}dz, \tag{2.18}$$

which requires the discounted flow of future trade balance deficits to equal the current stock of net foreign assets.

2.2.5 Macroeconomic Equilibrium

Because of a perfectly elastic supply of manufactured goods, any domestic excess demand for these goods can always be met on the world market. For the same reason, excess domestic supply of agricultural goods can be sold on the world market. As a result, the trade balance equation (2.17) is satisfied. Wage flexibility implies that labor supply by the representative household equals aggregate labor demand by firms in the two production sectors: $L(z) = L_M(z) + L_E(z)$.

Financial market equilibrium implies that $A(z) = V_K(z) + V_Z(z) + F(z)$, where $V_K(z) = q(z)K(z)$ denotes the stock market value of import-competing firms and $V_Z(z)$ is the value of the stock of land. Because all financial assets are assumed to be perfect substitutes, arbitrage ensures that the evolution of the value of land satisfies

$$rV_Z(z) = \dot{V}_Z(z) + r_Z(z)Z. \tag{2.19}$$

This condition requires that the return on land—consisting of the sum of the capital gain or loss $\dot{V}_Z(z)$ and rental income from land $r_Z(z)Z$—equals the return on assets.

2.3 Solving the Model

We derive the log-linearized reduced-form dynamic model and subsequently analyze its stability. All technical details are relegated to the Appendix.

2.3.1 Reduced-Form Model

We log-linearize the model of Section 2 around an initial steady state (Table 2.1). Tildes ($\tilde{}$) denote relative changes from the initial steady state for most variables (e.g., $\tilde{X}(z) \equiv dX(z)/X_0$), where X_0 denotes the initial steady-state value of

Table 2.1: Summary of the Log-Linearized Model

(a) Dynamic Equations:

$$\dot{\tilde{K}} = \frac{r\omega_I}{\omega_K}\left(\tilde{I}-\tilde{K}\right) \quad \text{(T1.01)}$$

$$\dot{\tilde{q}} = r\tilde{q} - \frac{\theta_K}{1-\theta_K}\frac{r\omega_L^M}{\sigma_M\omega_K}\left(\tilde{Y}_M-\tilde{K}+\sigma_M\tilde{\tau}_M\right) \quad \text{(T1.02)}$$

$$\dot{\tilde{F}} = r\left[\tilde{F}+\frac{\omega_L^M}{(1-\theta_K)(1+\tau_M)}\tilde{Y}_M+\frac{\omega_L^E}{1-\theta_Z}\tilde{Y}_E\right] - r\left[\frac{1}{1+t_C}\left(\frac{\omega_C^M}{1+\tau_M}\tilde{C}_M+\omega_C^E\tilde{C}_E\right)+\frac{\omega_I}{1+\tau_I}\tilde{I}\right] \quad \text{(T1.03)}$$

$$\dot{\tilde{V}}_Z = r\left(\tilde{V}_Z-\omega_Z\tilde{r}_Z\right) \quad \text{(T1.04)}$$

(b) Factor Markets and Production:

$$\tilde{L} = \sigma_{LL}\left(\tilde{w}-\tilde{X}\right) \quad \text{(T1.05)}$$

$$\omega_L\tilde{L} = \omega_L^E\tilde{L}_E+\omega_L^M\tilde{L}_M \quad \text{(T1.06)}$$

$$\tilde{w} = \tilde{\tau}_M+\frac{\theta_K}{\sigma_M}\left(\tilde{K}-\tilde{L}_M\right) = -\frac{\theta_Z}{\sigma_E}\tilde{L}_E \quad \text{(T1.07)}$$

$$\tilde{r}_Z = \frac{1-\theta_Z}{\sigma_E}\tilde{L}_E \quad \text{(T1.08)}$$

$$\tilde{q} = \chi_K\left(\tilde{I}-\tilde{K}\right) \quad \text{(T1.09)}$$

$$\tilde{Y}_M = \theta_K\tilde{K}+(1-\theta_K)\tilde{L}_M \quad \text{(T1.10)}$$

$$\tilde{Y}_E = (1-\theta_Z)\tilde{L}_E \quad \text{(T1.11)}$$

(c) Consumption, Goods Prices, and Revenue:

$$\tilde{C} = \tilde{X}-\tilde{p} \quad \text{(T1.12)}$$

$$\tilde{C}_M = \sigma_C\left(\tilde{p}-\tilde{p}_M\right)+\tilde{C}, \quad \tilde{C}_E=\sigma_C\left(\tilde{p}-\tilde{p}_E\right)+\tilde{C} \quad \text{(T1.13)}$$

$$\tilde{p} = \frac{\omega_C^M}{\omega_C}\tilde{p}_M+\frac{\omega_C^E}{\omega_C}\tilde{p}_E \quad \text{(T1.14)}$$

$$\tilde{p}_M = \tilde{t}_C+\tilde{\tau}_M, \qquad \tilde{p}_E=\tilde{t}_C \quad \text{(T1.15)}$$

$$\tilde{T} = t_L\omega_L\left(\tilde{w}+\tilde{L}\right)+\frac{\tau_I}{1+\tau_I}\omega_I\tilde{I}+\frac{t_C}{1+t_C}\omega_C^E\tilde{C}_E+\varepsilon_C\omega_X\tilde{t}_C + \frac{t_C+\tau_M(1+t_C)}{(1+t_C)(1+\tau_M)}\omega_C^M\tilde{C}_M-\frac{\tau_M}{(1+\tau_M)}\omega_L^M\tilde{Y}_M+\left(\omega_C^M-\frac{1}{1-\theta_K}\omega_L^M\right)\tilde{\tau}_M \quad \text{(T1.16)}$$

(d) Portfolio Equilibrium and Welfare:

$$\tilde{A} = \omega_K\left(\tilde{q}+\tilde{K}\right)+\tilde{V}_Z+\tilde{F} \quad \text{(T1.17)}$$

$$\tilde{U} = \tilde{X}-\tilde{p}_U, \quad \tilde{p}_U=\varepsilon\tilde{p}+(1-\varepsilon)\tilde{w} \quad \text{(T1.18)}$$

Notes: The following definitions are used: $\omega_C \equiv p_0C_0/Y_0$, $\omega_C^E \equiv (1+t_{C0})(C_E/Y)_0$, $\omega_C^M \equiv (1+t_{C0})(1+\tau_{M0})(C_M/Y)_0$, $\omega_I \equiv (1+\tau_{I0})I_0/Y_0$, $\omega_K \equiv (rqK)_0/Y_0$, $\omega_Z \equiv r_{Z0}Z_0/Y_0$, $\omega_L \equiv (wL)_0/Y_0$, $\omega_L^i \equiv (wL_i)_0/Y_0$ for $i=\{M,E\}$, $\sigma_{LL} \equiv (1-L_0)/L_0$, and $\chi_K \equiv -(I_0/K_0)(\Psi''/\Psi') > 0$, where $Y_0 \equiv p_0C_0+p_{I0}I_0-rF_0$ denotes steady-state GDP valued at market prices. A tilde ($\tilde{}$) denotes a relative change, for example, $\tilde{C}(z) \equiv dC(z)/C_0$. Time derivatives of variables are generally defined as $\dot{\tilde{X}}(z) \equiv d\dot{X}(z)/X_0$.

full consumption. Exceptions are financial variables and human wealth, which are scaled by output (e.g., $\tilde{A}(z) \equiv rdA(z)/Y_0$), lump-sum transfers ($\tilde{T}(z) \equiv dT(z)/Y_0$), and tax and tariff rates ($\tilde{t}_C(z) \equiv dt_C(z)/(1+t_{C0})$ and $\tilde{\tau}_M(z) \equiv d\tau_M(z)/(1+\tau_{M0})$). We assume that t_L and τ_I remain constant. Time derivatives of variables are generally defined as $\dot{\tilde{X}}(z) \equiv d\dot{X}(z)/X_0$, except for the time derivative of financial wealth and human capital, which are scaled by output (e.g., $\dot{\tilde{A}}(z) \equiv rd\dot{A}(z)/Y_0$). The log-linearized model can be condensed to a four-dimensional system of linear first-order differential equations. The dynamic system consists of two predetermined variables, $\tilde{K}(z)$ and $\tilde{F}(z)$, and two forward-looking variables, $\tilde{q}(z)$ and $\tilde{X}(z)$. All endogenous variables of the model can be expressed in terms of these state variables and the tax policy variables (Appendix 2.A.1).

The method of log-linearization does not allow us to study large shocks. Hence, we study a piecemeal cut in tariffs on consumption goods rather a wholesale removal of those tariffs.[16] The permanent and unanticipated cut in the import tariff rate on consumption goods (i.e., $\tilde{\tau}_M < 0$) causes an immediate change in government revenue.[17] Moreover, during transition, government revenue is affected by changes in the tax and tariff bases. We adjust the consumption tax rate such that the revenue effects of the reform are neutralized at each instant of time. Consequently, the domestic consumption tax rate becomes time varying. To determine the time path of the consumption tax rate, we first express the change in government revenue [$\tilde{T}(z)$ from (T1.16)] as a function of the four state variables, the domestic consumption tax rate, and the consumption tariff rate (Appendix 2.A.1). Subsequently, we impose $\tilde{T}(z) = 0$ and solve for the required change in the consumption tax rate:

$$\tilde{t}_C(z) = -\frac{1}{\phi_{TC}}\left(\xi_{TK}\tilde{K}(z) + \xi_{TQ}\tilde{q}(z) + \xi_{TX}\tilde{X}(0) + \phi_{TM}\tilde{\tau}_M\right). \tag{2.20}$$

The ξ_{Tj}'s (for $j = \{K, Q, X\}$) reflect pure tax-tariff base effects of the reform and the ϕ_{Tl}'s (for $l = \{C, M\}$) capture both rate and base effects.

If initial tax and tariff rates are zero (i.e., $t_{C0} = t_{L0} = \tau_{I0} = \tau_{M0} = 0$), there are no tax and tariff base effects so that only the rate effects remain. Hence, $\xi_{TK} = \xi_{TQ} = \xi_{TX} = 0$, in which case (2.20) reduces to: $\tilde{t}_C(z)/\tilde{\tau}_M = -\phi_{TC}/\phi_{TM}$. The term ϕ_{TC}/ϕ_{TM} is then unambiguously positive, so that a tariff rate cut induces

[16] Although a radial contraction of tariffs is theoretically interesting (cf. Hatzipanayotou et al., 1994), in practice, not many countries resort to such a strategy.

[17] The policy reform is unanticipated in the sense that the time of announcement and implementation of the policy change coincide. We normalize the time of the policy reform to zero.

a rise in the consumption tax rate. In this special case, the economy operates on the upward-sloping segment of the Laffer curve. Obviously, this result does not extend to all initial tax and tariff rates. High initial tax and tariff rates may cause a severe erosion of the consumption tax, labor income tax, and import tariff bases such that the economy ends up on the 'wrong side' of the Laffer curve. In our analysis, we set initial tax and tariff rates such that we find an equilibrium on the upward-sloping segment of the Laffer curve (see Section 2.5.1). As a result, the required change in the consumption tax rate is positive, i.e. $\tilde{t}_C(t) > 0$.

2.3.2 Dynamic System and Stability

To simplify the analysis, we split the dynamic system into an investment subsystem and a savings subsystem. Collecting the variables of interest in vectors, we can write the state variables of the investment subsystem as $\tilde{\mathbf{P}}_I(z) \equiv [\tilde{K}(z), \tilde{q}(z)]^\top$ and the state variables of the savings subsystem as $\tilde{\mathbf{P}}_S(z) \equiv [\tilde{X}(z), \tilde{F}(z)]^\top$, where $\top$ denotes a transpose. In the special case of exogenous labor supply, the model is recursive so that the investment subsystem can be solved independent of the savings subsystem. However, if labor supply is endogenous, we derive the solution to the investment subsystem conditional on $\tilde{X}(0)$. Subsequently, we solve the savings subsystem to obtain $\tilde{X}(0)$ and the time profile of $\tilde{F}(z)$. The dynamic equations describing the evolution of the economy are given by

$$\dot{\tilde{\mathbf{P}}}_I(z) = \Delta_I \tilde{\mathbf{P}}_I(z) + \Lambda_I[\tilde{X}(0), \tilde{\tau}_M]^\top, \tag{2.21a}$$

$$\dot{\tilde{\mathbf{P}}}_S(z) = \Delta_S \tilde{\mathbf{P}}_S(z) + \Lambda_S[\tilde{K}(z), \tilde{q}(z), \tilde{\tau}_M]^\top, \tag{2.21b}$$

where Δ_I and Δ_S denote the Jacobian matrices of the investment subsystem and savings subsystem, respectively:

$$\Delta_I \equiv \begin{bmatrix} 0 & \delta_{KQ} \\ \delta_{QK} & r \end{bmatrix}, \qquad \Delta_S \equiv \begin{bmatrix} 0 & 0 \\ \delta_{FX} & r \end{bmatrix},$$

where the matrix elements $\delta_{KQ} > 0$, $\delta_{QK} > 0$, and $\delta_{FX} < 0$ are defined in Appendix 2.A.2. The δ_{ij}'s are ceteris paribus effects of a change in state variables j with respect to the time derivatives of i, e.g. $\delta_{KQ} \equiv \partial\dot{\tilde{K}}/\partial\tilde{q}$. The λ_{ij}'s denote the ceteris paribus effects of a change in variables j exogenous to the relevant dynamic system with respect to the time derivatives of i, e.g. $\lambda_{FQ} \equiv \partial\dot{\tilde{F}}/\partial\tilde{q}$. Note that we have used (2.20) to eliminate $\tilde{t}_C(z)$ from (2.21a) and (2.21b). The matrices Λ_I and Λ_S on the right-hand side of (2.21a) and (2.21b) are given by

$$\Lambda_I \equiv \begin{bmatrix} 0 & 0 \\ \lambda_{QX} & \lambda_{QM} \end{bmatrix}, \qquad \Lambda_S \equiv \begin{bmatrix} 0 & 0 & 0 \\ \lambda_{FK} & \lambda_{FQ} & \lambda_{FM} \end{bmatrix}, \tag{2.22}$$

where the matrix elements $\lambda_{QX} > 0$, $\lambda_{QM} < 0$, $\lambda_{FK} \lesseqgtr 0$, $\lambda_{FQ} < 0$, and $\lambda_{FM} \gtrless 0$ are defined in Appendix 2.A.2. The row of zeros in the first matrix of (2.22) indicates that $\tilde{X}(0)$ only affects the investment subsystem via the $\dot{\tilde{q}}(z)$ locus. The sign of λ_{FK} is ambiguous. On the one hand, there is a positive effect of a larger capital stock on net foreign asset accumulation via: (i) a higher level of output (direct effect); and (ii) a reduced import tariff base, requiring an increase in the consumption tax rate to keep the reform revenue neutral, which in turn induces lower composite consumption (indirect effect). On the other hand, there is a negative effect of capital accumulation on net foreign asset accumulation: (i) directly through a rise in private investment; and (ii) indirectly via an expansion of the tariff base of imported capital goods. The latter enables the government to lower the consumption tax rate in a revenue-neutral fashion, which leads to higher composite consumption. The ambiguity of the sign of λ_{FM} originates from two opposing effects on net foreign assets induced by an increase of the import tariff rate: (i) a direct positive effect, reflecting an increase in output and a decrease in composite consumption; and (ii) an indirect negative effect through an increased labor income tax base. The latter enables the government to lower the consumption tax rate in a revenue-neutral fashion, which leads to higher composite consumption. Assumption 1, which holds for plausible parameter values, pins down the signs of λ_{FK} and λ_{FM}.

Assumption 1. The direct output effect dominates the other effects, so that: (i) the effect of the capital stock on net foreign asset accumulation is positive (i.e., $\lambda_{FK} > 0$); and (ii) the effect of the import tariff rate on net foreign asset accumulation is positive (i.e., $\lambda_{FM} > 0$). A sufficient condition for (ii) to hold is $\sigma_{LL} > \frac{t_L}{1-t_L}$, where σ_{LL} is the labor supply elasticity.

The steady state of the system is denoted by $\dot{\tilde{\mathbf{P}}}_I(z) = \dot{\tilde{\mathbf{P}}}_S(z) = 0$. Note that the knife-edge condition $r = \rho$ implies a zero root in full consumption; that is, the first row of Δ_S consists of zeros. Consequently, we obtain a hysteretic steady state. The stability properties of the model are summarized in Proposition 2.1.

Proposition 2.1. *The dynamic system is locally saddle-point stable and features a hysteretic steady state. It can be decomposed in two interdependent subsystems—one for investment and one for savings—with the following properties:*

(i) the investment subsystem has two distinct real eigenvalues; that is, $-h_1^* < 0$ *and* $r_1^* = r + h_1^* > 0$ *with* $\partial h_1^*/\partial \chi_K < 0$, $\lim_{\chi_K \to 0} h_1^* = \infty$, *and* $\lim_{\chi_K \to \infty} h_1^* = 0$*; and*

(ii) the savings subsystem has two distinct real eigenvalues; that is, $h_2^* = 0$ *and* $r_2^* = r > 0$.

Proof. See Appendix 2.A.2. □

2.4 Graphical Analysis

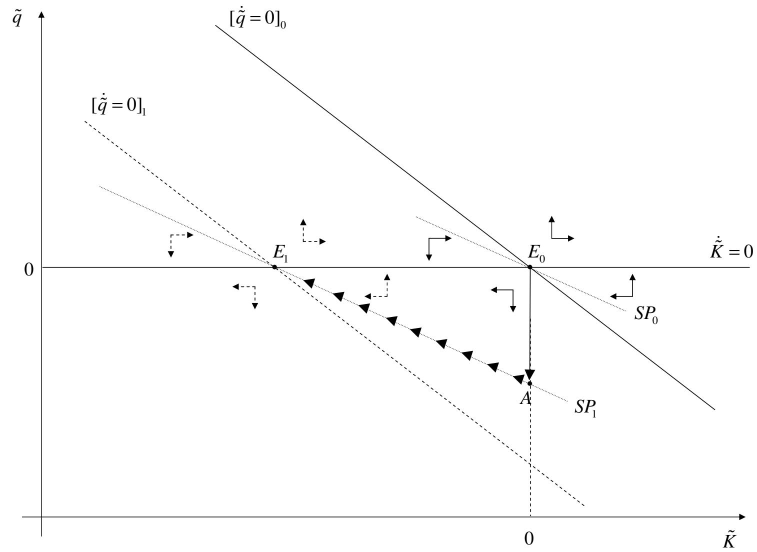
Section 2.4.1 develops a graphical apparatus and Section 2.4.2 uses this framework to analyze the allocation effects of the proposed tax-tariff reform.

2.4.1 Graphical Apparatus

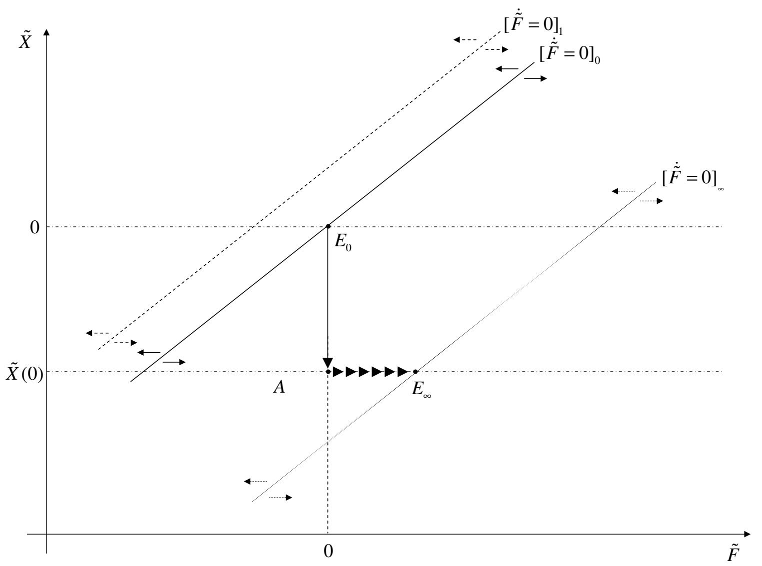
Panel (a) of Figure 2.1 shows the phase diagram for the investment subsystem. The capital stock equilibrium (CSE) locus—given by $\dot{\tilde{K}}(z) = 0$—represents combinations of $\tilde{K}(z)$ and $\tilde{q}(z)$ for which net investment is zero so that the capital stock is constant. It follows from (2.12) and (2.14b) that this only occurs if Tobin's q equals its steady-state value, implying that the CSE locus is horizontal at $\tilde{q} = 0$. If Tobin's q is above this line net investment will be positive, which is indicated by the horizontal arrows in the figure. The investment plan equilibrium (IPE) locus—given by $\dot{\tilde{q}}(z) = 0$—gives combinations of $\tilde{K}(z)$ and $\tilde{q}(z)$ for which Tobin's q is constant over time. The IPE schedule is negatively sloped, because an increase in the capital stock depresses the marginal product of capital so that its value in equilibrium will be lower. For points to the right of the IPE schedule, the marginal product of capital is too low, so that part of the return to capital consists of capital gains. Conversely, for points to the left of the IPE schedule, the marginal product of capital is too high, giving rise to capital losses on investment. Hence, $\dot{\tilde{q}}(z) > 0$ to the right of the locus and $\dot{\tilde{q}}(z) < 0$ to the left, as represented by the vertical arrows in the figure. The arrow configuration for the CSE and IPE schedules confirms that the equilibrium at E_0 is saddle-point stable.

Figure 2.1: Phase Diagrams: The Investment and Savings System

(a) Investment System



(b) Savings System



Notes: The model is non-recursive in the case of endogenous labor supply. The solution to the investment subsystem—which is depicted in Panel (a)—is conditional on $\tilde{X}(0)$ and Assumption 2. Panel (b) depicts the case in which $\lambda_{FQ}\tilde{q}(0) + \lambda_{FM}\tilde{\tau}_M > 0$ and $\tilde{X}(0) < 0$. Because the model is log-linearized, we can depict linear relationships and report the relative changes of variables on the axes. The initial equilibrium is located in the $(0, 0)$ point.

Panel (b) of Figure 2.1 represents graphically the savings subsystem. The condition $r = \rho$ ensures that $\dot{\tilde{X}}(z) = 0$ irrespective of $\tilde{F}(z)$ and $\tilde{X}(z)$. Hence, only the net foreign assets (NFA) locus—given by $\dot{\tilde{F}}(z) = 0$—is drawn, which gives combinations of $\tilde{F}(z)$ and $\tilde{X}(z)$ that yield a constant stock of net foreign assets. The locus has a positive slope, because a higher steady-state level of full consumption can only be sustained if the stock of net foreign assets increases. For points above the line, full consumption is too high, so that net foreign assets decrease over time. Conversely, for points below the line, full consumption is too low, implying an increasing stock of net foreign assets.

2.4.2 Allocation Effects

We discuss the allocation effects of the revenue-neutral tax-tariff reform by using the phase diagrams in Panels (a) and (b) of Figure 2.1 and the labor market equilibrium in Figure 2.2. Analytical expressions for the time paths of the state variables are derived in Appendix 2.A.2.

Investment Subsystem Panel (a) of Figure 2.1 shows that the reform shifts the IPE locus down from $[\dot{\tilde{q}} = 0]_0$ to $[\dot{\tilde{q}} = 0]_1$. The capital stock locus remains unaffected. For a given capital stock, Tobin's q jumps down from E_0 to A, reflecting a decrease in the marginal product of capital. Two opposing effects are at work: a direct price effect and an indirect wealth effect. The direct price effect causes Tobin's q to fall via a lower producer price of manufactured goods. The indirect wealth effect positively affects Tobin's q through its impact on labor supply. Under plausible parameter values, the indirect wealth effect on the IPE locus falls short of the direct price effect (Assumption 2).[18] Tobin's q recovers over time as the capital stock decreases during transition to the new equilibrium E_∞. In the long run, Tobin's q is back at its initial value, but the capital stock is permanently lower.

Assumption 2. The direct negative effect of the fall in the producer price p_M on the marginal product of capital dominates the potentially counteracting indirect effect operating through the wealth effect on labor supply: $|\lambda_{QM}\tilde{\tau}_M| > |\lambda_{QX}\tilde{X}|$.

[18] Although a formal proof is lacking, a numerical inspection did not yield any instances violating the assumption.

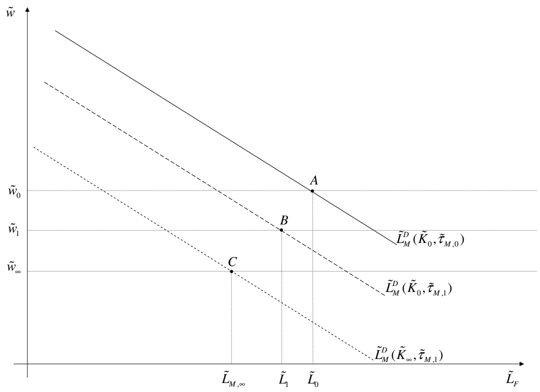
Savings Subsystem Assumptions 1 and 2 ensure that $\lambda_{FQ}\tilde{q}(0)+\lambda_{FM}\tilde{\tau}_M > 0$, so that on impact the tax tariff reform shifts the NFA curve upward, from $[\dot{\tilde{F}} = 0]_0$ to $[\dot{\tilde{F}} = 0]_1$ in Panel (b) of Figure 2.1. Over time, as the capital stock decreases, the NFA locus shifts down, owing to declining aggregate output. Eventually, the NFA locus even shifts down beyond its initial position to $[\dot{\tilde{F}} = 0]_\infty$. Full consumption jumps to a point below $[\dot{\tilde{F}} = 0]_1$ and in all considered scenarios this point is also below E_0. It follows that full consumption immediately falls as the economy jumps from E_0 to A. Subsequently, during transition, the stock of net foreign assets increases to reach a higher long-run value at E_∞.

Labor Market Panels (a) and (b) of Figure 2.2 depict the labor demand schedules for the import-substitution sector and the export sector, respectively [see (T1.07)]. Panel (c) shows the aggregate (Frisch) labor supply curve together with the aggregate labor demand, which are given by (T1.05) and (T1.06), respectively. The cut in the import tariff on consumption decreases labor demand by firms in the import-substitution sector, which is represented by an inward shift in the labor demand schedule from $\tilde{L}_M^D(\tilde{K}_0, \tilde{\tau}_{M,0})$ to $\tilde{L}_M^D(\tilde{K}_0, \tilde{\tau}_{M,1})$ in Panel (a). The labor demand curve of firms in the export sector in Panel (b) remains unaffected. Hence, aggregate labor demand [see Panel (c)] shifts to the left. The aggregate labor supply curve shifts to the right, as a result of the wealth effect on labor supply; that is, households supply more labor because they experience a fall in wealth. The accompanying increase in the consumption tax rate dampens the wealth effect, because it increases the price of the composite consumption good. On impact, workers relocate from the import-substitution sector to the export sector and the equilibrium real wage rate falls. Employment in the export sector goes up immediately. The sign of the change in aggregate employment depends on the magnitude of the shift of the aggregate labor supply curve relative to that of the aggregate labor demand curve. The figure shows the case in which aggregate employment jumps up, in accordance with the results that we find in our numerical analysis in Section 2.5.

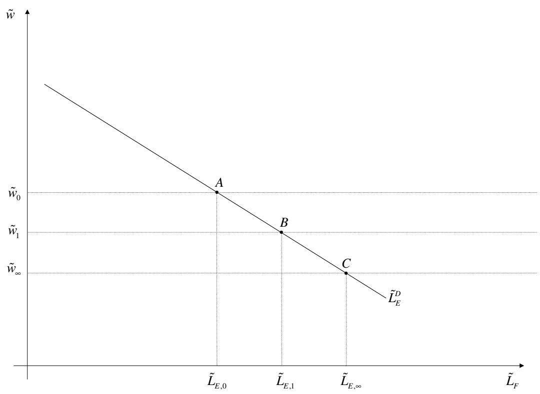
Over time, the labor demand curve of the import-substitution sector shifts further to the left as the capital stock decreases. Because the labor demand curve of the export sector remains unaffected again, the aggregate labor demand curve shifts leftward as well. Consequently, employment in the import-substitution sector and aggregate employment both decline over time. The decreasing capital stock—and the associated lower labor productivity—in the import-substitution

Figure 2.2: Aggregate and Sectoral Labor Market Equilibrium

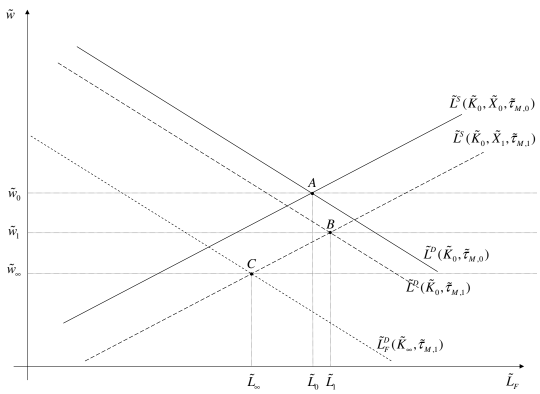
(a) Import-Substitution Sector



(b) Agricultural Sector



(c) Aggregate Labor Market



Notes: Panels (a) and (b) are based on equation (T1.07) and Panel (c) on equations (T1.05)–(T1.06). The dashed and dotted lines represent short-run and transitional responses, respectively. Panel (c) shows the case where the downward shift in short-run labor supply dominates the downward shift in short-run labor demand.

sector ensures that workers relocate from the import-substitution to the export sector, boosting long-run employment in the export sector. In the long run, the real wage rate is lower than before the reform. The sign of the change in long-run aggregate employment again depends on the magnitude of the shift of the aggregate labor supply curve (wealth effect) relative to that of the aggregate labor demand curve (productivity effect). The figure shows the case in which long-run aggregate employment goes down, in accordance with our numerical results in the next section.

2.5 Numerical Analysis

To obtain insight into the quantitative allocation and welfare effects of the proposed revenue-neutral tax-tariff reform, Section 2.5.1 calibrates the model and Sections 2.5.2 and 2.5.3 perform a numerical simulation.

2.5.1 Calibration

We calibrate the model to match important characteristics of a typical developing open economy in the low-income group. Table 2.2 contains an overview of the calibration parameters. The tax and tariff rates are chosen such that the revenue shares of the tax instruments are in line with the data.[19] The decade averages of the revenue shares of the consumption tax, labor income tax, and tariffs in total tax revenue are 48, 22, and 30 percent, respectively (World Bank, 2010). Given that final goods generally bear a higher tariff rate than capital goods, we impose a tariff rate on consumption goods of 15 percent and a tariff rate on capital goods of 7.5 percent. The implied consumption tax rate and labor income tax rate are 9 percent and 7 percent, respectively. The implied tax revenue-to-GDP share is 16 percent (Table 2.3), which is within the range of 14.1 to 16.7 percent that Gordon and Li (2009) report for low-income and middle-income countries, respectively.

In line with Gollin (2002a), the labor income share in the import-substitution sector $(1-\theta_K)$ is set to 0.7. Following Valentinyi and Herrendorf (2008), the labor income share in agriculture $(1-\theta_Z)$ takes on a lower value than that of the aggregate economy, owing to a large land income share. We set the labor income

[19] Because of exemptions, tax evasion, and the like, the collected tariff rate—defined as tariff revenue divided by the import value—is smaller than the statutory tariff rate. Our chosen tax and tariff rates are therefore lower bounds of actual statutory tax and tariff rates.

share in the agricultural sector to 0.5. The parameter Z is chosen such that the employment share of the agricultural sector amounts to around 65 percent, which is the average for low-income countries over the last decade (World Bank, 2010).

Empirical estimates of the input substitution elasticities in production cover a wide range. Salhofer (2000) reviews studies on the substitution elasticity between land and labor and reports a weighted mean value of 0.3, with a standard deviation of 0.5. For the substitution elasticity between capital and labor, Chirinko (2008) concludes that it varies between 0.4 and 0.6. In view of these results, we set the substitution elasticity between land and labor to 0.3 and between capital and labor to 0.5.

We follow Mendoza (1995) by setting the rate of capital depreciation (δ) to 10 percent, but choose a real rate of interest (r) of 5 percent, which is one percentage point above Mendoza's value. The concave adjustment cost function is assumed to have a logarithmic form:

$$\Psi\left(\frac{I}{K}\right) = \bar{z}\left[\ln\left(\frac{I}{K} + \bar{z}\right) - \ln \bar{z}\right], \tag{2.23}$$

where $\bar{z}$ is a parameter that regulates the concavity of the function and therefore the magnitude of the adjustment costs. By choosing $\bar{z} = 2$, we obtain adjustment costs equal to 0.2 percent of GDP, which is slightly above Mendoza (1991), who works with a ratio of 0.1 percent of GDP for the Canadian economy.

The intertemporal substitution elasticity of labor supply (i.e., $\sigma_{LL} \equiv (1 - L_0)/L_0$) is equal to the so-called Frisch elasticity of labor supply. Using micro data, Kimball and Shapiro (2008) find estimates of the Frisch elasticity of about one. Real business cycles (RBC) studies (e.g., Mendoza, 1991; and Prescott, 2006), however, typically work with Frisch elasticities of at least two. We set $\sigma_{LL} \equiv (1 - L_0)/L_0 = 2.25$, which is in accordance with the RBC literature. Assuming a daily time endowment of 16 hours, $\sigma_{LL} = 2.25$ corresponds to 1,800 annual hours worked per worker.[20] We set $\sigma_C = 0.5$, which is in line with the smaller than unitary elasticities found by Dennis and Iscan (2007). For the preference parameters γ and ε, we pick values to get an implied imports-to-GDP ratio of 41 percent, which is equal to the decade average in low-income countries (World Bank, 2010). We find an implied export-to-GDP ratio of 40 percent, which is

[20] Although not much data for low-income countries are available, this number is close to the average of 1,821 annual hours worked per worker for the 13 countries with a per capita income below 15,000 US dollars (PPP-adjusted) in 2010 (The Conference Board, 2011)

Table 2.2: The Parameter Values in the Benchmark Scenario

Description	Parameter	Value	Source
Tax policy parameters			
Consumption tax rate	t_C	0.090	Gordon and Li (2009)
Labor income tax rate	t_L	0.070	Gordon and Li (2009)
Import tariff rate on capital goods	τ_I	0.075	Gordon and Li (2009)
Import tariff rate on consumption goods	τ_M	0.150	Gordon and Li (2009)
Technology			
Weight given to capital in M sector	α_M	0.500	Data: World Bank (2010)
Weight given to land in E sector	α_E	0.500	Data: World Bank (2010)
Elasticity of substitution in M sector	σ_M	0.500	Chirinko (2008)
Elasticity of substitution in E sector	σ_E	0.300	Salhofer (2000)
Land (fixed)	Z	0.200	Data: World Bank (2010)
Capital accumulation			
Rate of interest	r	0.050	Mendoza (1995)[a]
Rate of depreciation	δ	0.100	Mendoza (1995)
Adjustment cost parameter	$\bar{z}$	2.000	Mendoza (1991)
Preferences[b]			
Weight given to M goods	γ	0.800	Data: World Bank (2010)
Elasticity of substitution in consumption	σ_C	0.500	Data: World Bank (2010)
Intertemporal labor supply elasticity	σ_{LL}	2.250	Mendoza (1991), The Conference Board (2010)
Weight given to consumption	ε	0.475	Data: World Bank (2010)

Notes: [a]We chose a slightly higher value than Mendoza (1995). [b]The pure rate of time preference is equal to the real rate of interest in the steady state and is therefore not reported separately.

Table 2.3: Implied Shares, Parameters, and Ratios in the Benchmark Scenario

Description	Parameter	Value
Productivity index of M sector	Ω_M	0.81
Productivity index of E sector	Ω_E	1.82
Capital-output ratio of M sector	K/Y_M	2.06
Capital-output ratio of overall economy	K/Y	0.52
GDP share of return on financial wealth	ω_A	0.31
GDP share of composite consumption	ω_C	0.92
GDP share of consumption good E	ω_C^E	0.29
GDP share of consumption good M	ω_C^M	0.63
GDP share of net foreign assets	ω_F	-0.59
GDP share of investment	ω_I	0.05
GDP share of capital income	ω_K	0.02
GDP share of total labor income	ω_L	0.48
GDP share of labor income of M sector	ω_L^M	0.17
GDP share of labor income of E sector	ω_L^E	0.32
GDP share of government revenue	ω_T	0.16
GDP share of imports	ω_{IM}	0.41
GDP share of exports	ω_{EX}	0.40
Revenue share of consumption tax	ω_C^T	0.48
Revenue share of labor income tax	ω_L^T	0.22
Revenue share of import tariff on I	ω_I^T	0.02
Revenue share of import tariff on C_M	ω_M^T	0.28
GDP share of land rentals	ω_Z	0.32

Notes: The following definitions are used: $\omega_{IM} = [p_{M0}(C_{M0} - Y_{M0}) + p_{M0}I_0]/Y_0$, $\omega_{EX} = p_{E0}(Y_{E0} - C_{E0})/Y_0$, $\omega_F \equiv F_0/Y_0$, $\omega_T^C \equiv t_{C0}[C_{E0} + (1 + \tau_{M0})C_{M0}]/T_0$, $\omega_T^L \equiv t_{L0}w_0L_0/T_0$, $\omega_T^I \equiv \tau_{I0}I_0/T_0$, and $\omega_T^M \equiv \tau_{M0}(C_{M0} - Y_{M0})/T_0$, where $Y_0 \equiv p_0C_0 + p_{I0}I_0 - rF_0$ denotes steady-state GDP valued at market prices. The other shares are defined in Table 2.1.

considerably higher than the 10-year average share of manufacturing imports in GDP of 24 percent for low-income countries. The discrepancy is a result of the imposed current account equilibrium in the initial steady state.

Using World Bank (2010) data, gross fixed capital formation as a share of GDP was on average 19 percent in low-income countries during the last decade. Our implied investment-to-GDP ratio of 5 percent is considerably lower than this number, but does not seem unreasonable given that: (i) our model does not feature public investment; and (ii) investment is only possible in the import-substitution sector, where the investment-to-output ratio equals 18 percent. The implied share of consumption in GDP amounts to 92 percent, which is somewhat lower than the average share of 98 percent of household final consumption expenditure in GDP in low-income countries during the last decade.

2.5.2 Allocation Effects

Table 2.4 presents the short-run and long-run allocation effects of the reform. Three scenarios are being distinguished. The first scenario (labeled $\sigma_{LL} = 2.25$) presents the benchmark, which sets all parameter values in accordance with Table 2.2. In the second scenario (labeled $\sigma_{LL} = 0$), we investigate the case of exogenous labor supply to emphasize the importance of allowing endogenous labor supply in our benchmark case. Scenario three (labeled $\sigma_E = \sigma_M = 1$) restricts the production functions to a Cobb-Douglas specification, which is commonly used in the literature. We will first discuss the benchmark scenario and subsequently highlight the most important differences between scenarios.

Benchmark Scenario The wealth panel of Table 2.4 shows that households experience a fall in human capital, but enjoy an increase in the value of their financial wealth holdings in the short run as well as in the long run. Moreover, within their financial wealth portfolio a reallocation from investment in domestic capital toward foreign assets occurs in the long run. Because of the positive employment effect in the export sector, the value of land jumps up immediately and further increases over time.

The labor market panel of Table 2.4 shows—in line with our discussion in Section 2.4.2—that aggregate employment rises immediately. Intuitively, the reform induces an increase in labor supply induced by the negative wealth effect on labor supply, which is driven by the considerable fall in human capital. Over time, the real wage rate decreases as the capital-labor ratio falls. Because labor and capital are cooperative factors, the fall in physical capital leads to a negative aggregate employment effect in the long run. Reallocation of workers from the import-substitution sector to the export sector increases employment in the latter sector, more so in the long run than in the short run. The immediate increase in aggregate employment leads to a rise in aggregate output, as shown in the production panel of Table 2.4. Moreover, the improved allocation of workers across sectors amplifies the initial positive effect on aggregate production. Qualitatively, the sectoral output responses are similar to the employment effects in both sectors.

Table 2.4: Short-Run and Long-Run Allocation Effects

	$\sigma_{LL} = 2.25$		$\sigma_{LL} = 0$		$\sigma_E = \sigma_M = 1$	
	0	∞	0	∞	0	∞
	(1)	(2)	(3)	(4)	(5)	(6)
Wealth						
$\tilde{A}$	0.468	0.671	0.490	0.532	0.443	0.723
$\tilde{H}$	-2.287	-2.489	-0.723	-0.766	-2.209	-2.489
$\tilde{F}$	0.000	0.323	0.000	0.064	0.000	0.507
$\tilde{K}$	0.000	-6.402	0.000	-2.306	0.000	-10.909
$\tilde{q}$	-0.799	0.000	-0.546	0.000	-1.107	0.000
$\tilde{V}_Z$	0.492	0.535	0.506	0.535	0.475	0.535
Labor market						
$\tilde{L}_M$	-0.444	-5.687	-0.668	-1.592	-1.271	-9.495
$\tilde{L}_E$	0.440	0.857	0.360	0.857	1.217	2.829
$\tilde{L}$	0.131	-1.433	0.000	0.000	0.346	-1.485
$\tilde{w}$	-0.733	-1.429	-0.599	-1.429	-0.615	-1.429
Production						
$\tilde{Y}_M$	-0.311	-5.902	-0.467	-1.806	-0.890	-9.919
$\tilde{Y}_E$	0.220	0.429	0.180	0.429	0.609	1.414
$\tilde{Y}$	0.087	-1.158	0.018	-0.132	0.233	-1.426
Consumption						
$\tilde{C}_M$	-0.542	-0.368	0.178	0.238	-0.504	-0.197
$\tilde{C}_E$	-1.042	-0.868	-0.322	-0.262	-1.004	-0.697
$\tilde{C}$	-0.701	-0.527	0.019	0.079	-0.663	-0.356
$\tilde{p}$	-0.091	-0.265	-0.241	-0.301	-0.106	-0.413
Investment						
$\tilde{I}$	-16.379	-6.402	-11.188	-2.306	-22.704	-10.909
Market access						
$\tilde{IM}$	-1.115	0.920	-0.376	0.466	-1.283	1.789
$\tilde{EX}$	0.497	0.597	0.234	0.402	0.776	1.282
Fiscal sector						
$\tilde{t}_C$	0.591	0.417	0.441	0.381	0.576	0.269

Notes: Tildes denote relative changes, except for *IM*, *EX*, and t_C where we define $\tilde{IM} = dIM/Y_0^*$, $\tilde{EX} = dEX/Y_0^*$, and $\tilde{t}_C = dt_C/(1+t_C)$. Y_0^* denotes aggregate steady-state output at world market prices. All parameters are set at their benchmark values in columns (1)–(2). Columns (3)–(4) set $\varepsilon = 1$, so that labor supply is exogenous (i.e., $\sigma_{LL} = 0$). Columns (5)–(6) correspond to Cobb-Douglas production functions, that is, $\sigma_E = \sigma_M = 1$. Note that columns (3) and (5) have been recalibrated (via adjustments in the stock of land) to arrive at the benchmark steady state. The policy shock consists of $\tilde{\tau}_M = -0.01$, where $\tilde{t}_C$ is being determined endogenously to keep government revenue unchanged.

Because households experience a wealth loss in the short run, they cut back on their consumption of both commodities immediately. Compared to the manufacturing good, consumption of the agricultural good goes down by more, owing to an increase in the relative consumer price of agricultural goods. Over time, aggregate consumption increases because of a transitional decline in the consumption tax rate (see below). The long-run effect on consumption, however, remains negative. Market access, which is defined as the sum of imports and exports, decreases immediately as a result of the substantial fall in investment, but increases in the long run when both imports and exports are higher than before the reform.

To compensate for the tightening of all four tax bases and the tariff rate decline, the consumption tax rate has to rise in the short run. During transition, a broadening of both import tariff bases and the consumption tax base takes place, which dominates the revenue effect of the shrinking labor tax base, so that the required long-run increase in the consumption tax rate falls short of its short-run rise.

Exogenous Labor Supply The second scenario sets the elasticity of labor supply (σ_{LL}) to zero, so that the positive short-run effect and the negative long-run effect on employment disappear. As a result, the short-run fall in the real wage rate and in human capital are less pronounced than for $\sigma_{LL} > 0$ which, together with the downward jump in the price index, increase composite consumption in the short run. The jump in consumption broadens the consumption tax base, thereby yielding a smaller required increase in the consumption tax rate than in the benchmark scenario. The short-run increase in aggregate production can now be fully attributed to a more efficient allocation of a given stock of labor across the sectors. Combining (T1.10), (T1.11), (A.2.3), and (A.2.4), and using $\tilde{K}(0) = \sigma_{LL} = 0$, this can be shown by:

$$\frac{\tilde{Y}(0)}{\tilde{\tau}_M} = -\frac{\omega_L^M \omega_L^E}{|\Omega|} \frac{\tau_M}{1 + \tau_M}, \tag{2.24}$$

where ω_L^M and ω_L^E denote the GDP share of labor income in the import-substitution and export sector, respectively. The right-hand-side of equation (2.24) is negative if $\tau_M > 0$ (because $|\Omega| > 0$, see Appendix A.1).

Because aggregate labor supply remains constant, capital decumulation will be less severe so that aggregate output decreases by a relatively smaller amount in the long run. The steady-state marginal product of capital is determined by the real interest rate on the world market, which in turn—via the factor price frontier—determines the long-run capital-labor ratio and the real wage rate. Therefore, the long-run fall in the real wage rate is not affected by the elasticity of labor supply [compare columns (2) and (4)]. Net foreign assets increase by less than in the benchmark scenario, reflecting a smaller fall in domestic investment.

Cobb-Douglas Specification Qualitatively, the responses to the reform do not change between the Cobb-Douglas scenario [see columns (5)–(6)] and the benchmark case. Imposing a unitary elasticity of substitution between factors of production amplifies the responses on the production side. The long-run effects on the stock of physical capital and output in the import-competing sector are noticeably larger than in the benchmark scenario. As a result, the tax base of the tariff on imported consumption goods increases substantially over time, leading to a large drop in the required long-run change in the consumption tax rate.

2.5.3 Welfare Effects

This section discusses the welfare effects of the revenue-neutral tax-tariff reform. In view of the exogenously imposed revenue requirement, the first-best outcome with zero tax and tariff rates cannot be achieved. In fact, the initial equilibrium is not even second best, given that the pre-existing tax and tariff rates are set such that they are representative of a typical developing economy. In this case, reducing one distortion does not necessarily improve welfare (Lipsey and Lancaster, 1957). The interactions between different distortions are complex, because the initial tax system does not only have static efficiency effects—by affecting relative goods prices and the relative price of consumption and leisure—but also lead to intertemporal distortions by influencing the investment decision of firms and the household's intertemporal allocation of consumption and labor supply. To determine the sign of the welfare change induced by the reform, we conduct a numerical analysis. Before venturing into the numerical illustration, we first discuss our welfare measure.

By substituting (2.4) and (2.6a) into (2.1), lifetime utility of the representative household can be written as:

$$\Lambda(0) \equiv \int_0^\infty \ln\left[\frac{X(z)}{p_U(z)}\right] e^{-\rho(z-t)} dz, \tag{2.25}$$

where the ideal price index of utility is given by:

$$p_U(z) \equiv \Omega_U p(z)^{\varepsilon} \left[(1-t_L)w(z)\right]^{1-\varepsilon}, \quad \Omega_U \equiv \left[\varepsilon^{\varepsilon}(1-\varepsilon)^{1-\varepsilon}\right]^{-1} > 0. \tag{2.26}$$

By taking the total differential of lifetime utility (2.25) and using (2.26), we arrive at our measure of welfare change:

$$d\Lambda(0) = \frac{\tilde{X}(0)}{\rho} - \frac{\rho \tilde{p}_U(0) + h_1^* \tilde{p}_U(\infty)}{\rho(\rho + h_1^*)}, \qquad \tilde{p}_U(z) = \varepsilon \tilde{p}(z) + (1-\varepsilon)\tilde{w}(z). \tag{2.27}$$

The first term on the right-hand side of (2.27) denotes the welfare effect of the jump in full consumption to its new equilibrium value. The welfare effect owing to the transitional change of the utility price index is captured by the second term. To show the importance of the dynamic dimension of our analysis, we decompose the welfare effect into a static component $d\Lambda_S(0)$ and a dynamic component $d\Lambda_D(0)$. To obtain the static welfare effect, we eliminate physical capital accumulation from the model, so that physical capital becomes de facto a fixed factor. We model the fixed factor by setting $\chi_K \to \infty$, which implies $\bar{z} \to 0$.

Table 2.5 displays the short-run and long-run effects on instantaneous utility (denoted by $\tilde{U}(0)$ and $\tilde{U}(\infty)$, respectively, and $\tilde{U}(t) = \tilde{X}(t) - \tilde{p}_U(t)$) and the resulting change in lifetime utility $d\Lambda(0)$ (i.e., the present discounted value of utility). We again study the three scenarios set out in Table 2.4. In the benchmark scenario, instantaneous utility decreases on impact, recovers gradually over time, and eventually settles down at a higher steady-state level. Intuitively, the anticipated future decline in the real wage rate—and the associated fall in full consumption—induces households to cut back on leisure consumption. During transition, labor supply falls as the real wage rate decreases thereby decreasing composite consumption. Moreover, the utility price index is decreasing over time, reflecting a falling composite consumption price index and real wage rate. Both the dynamic and the static component of the change in lifetime utility are positive, although the dynamic component is smaller than the static component.

In the scenario with exogenous labor supply [columns (3)–(4)], the increase in welfare is considerably larger, because the negative short-run effect on instantaneous utility disappears. Intuitively, the household no longer derives utility from leisure so that the distortion of the household's intertemporal labor supply decision cannot occur. In the scenario with Cobb-Douglas production functions [columns (5)–(6)], the welfare change is also larger than in the benchmark case. The reason is that the intertemporal distortion of the import tariff is larger the higher is the substitutability of inputs in production. Therefore, in both alternative scenarios, especially the dynamic part of the welfare change increases compared to the benchmark case.

It is well known that the welfare effects of tax policy changes in an nth best setting depend crucially on pre-existing tax and tariff distortions. Therefore, we show the effect of changes in pre-existing tax and tariff rates on lifetime utility. Panel (a) of Figure 2.3 depicts the welfare change for different combinations of the consumption tax rate and the import tariff rate. In line with intuition, the welfare change depends positively on the initial import tariff rate and negatively on the initial consumption tax rate. The intersection of the welfare plane with the $d\Lambda(0) = 0$ plane indicates that the welfare change becomes negative if the pre-existing import tariff rate is small, or if the pre-existing consumption tax rate is high.

Table 2.5: Welfare Effects

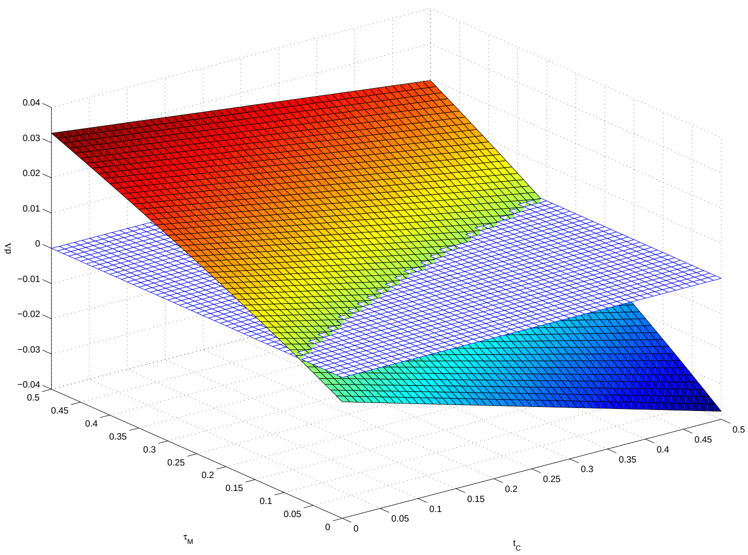
	$\sigma_{LL} = 2.25$		$\sigma_{LL} = 0$		$\sigma_E = \sigma_M = 1$	
	0	∞	0	∞	0	∞
	(1)	(2)	(3)	(4)	(5)	(6)
$\tilde{X}$	-0.791	-0.791	-0.222	-0.222	-0.769	-0.769
$\tilde{p}_U$	-0.428	-0.876	-0.241	-0.301	-0.373	-0.946
$\tilde{U}$	-0.363	0.084	0.019	0.079	-0.396	0.177
$d\Lambda$	0.190	-	1.418	-	1.282	-
$d\Lambda_S$	0.176	-	0.706	-	0.463	-
$d\Lambda_D$	0.014	-	0.712	-	0.819	-

Notes: Using equation (1), we can derive $\tilde{U}(t) = \tilde{X}(t) - \tilde{p}_U(t)$ and $d\Lambda(0)$, where $d\Lambda(0)$ denotes the change in total lifetime utility, $d\Lambda_S(0)$ denotes the change in the static component, and $d\Lambda_D(0)$ is the change in the dynamic component. All parameters are set at their benchmark values in columns (1)–(2). Columns (3)–(4) set $\varepsilon = 1$, so that labor supply is exogenous (i.e., $\sigma_{LL} = 0$). Columns (5)–(6) correspond to Cobb-Douglas production functions, that is, $\sigma_E = \sigma_M = 1$. The policy shock consists of $\tilde{\tau}_M = -0.01$, where $\tilde{t}_C$ is being determined endogenously to keep government revenue unchanged.

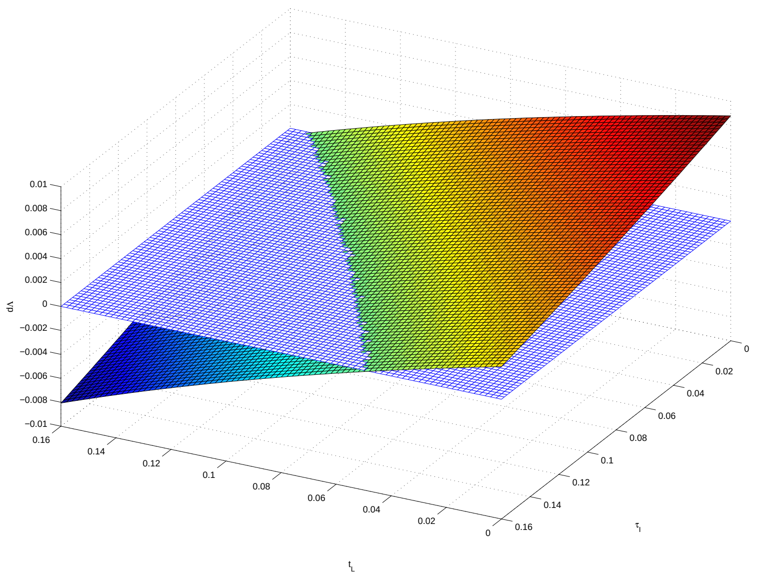
Panel (b) of the figure shows that the welfare change is negatively affected by the pre-existing labor income tax rate. Intuitively, both the labor income tax and the consumption tax distort the relative price of consumption and leisure. Therefore, a high pre-existing labor income tax rate makes the required increase in the revenue-neutral consumption tax rate more distortionary. Panel (b) also

Figure 2.3: Welfare Effects of Coordinated Tax-Tariff Reform

(a) Different Pre-existing t_C and τ_M



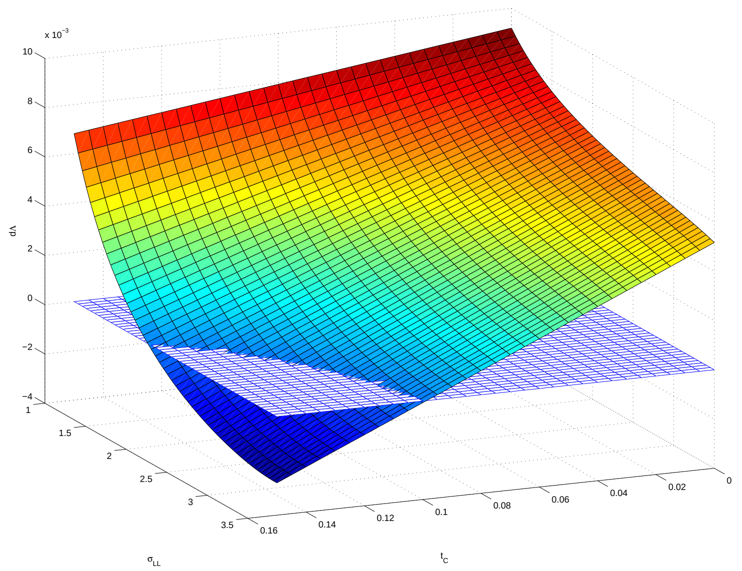
(b) Different Pre-existing τ_I and t_L



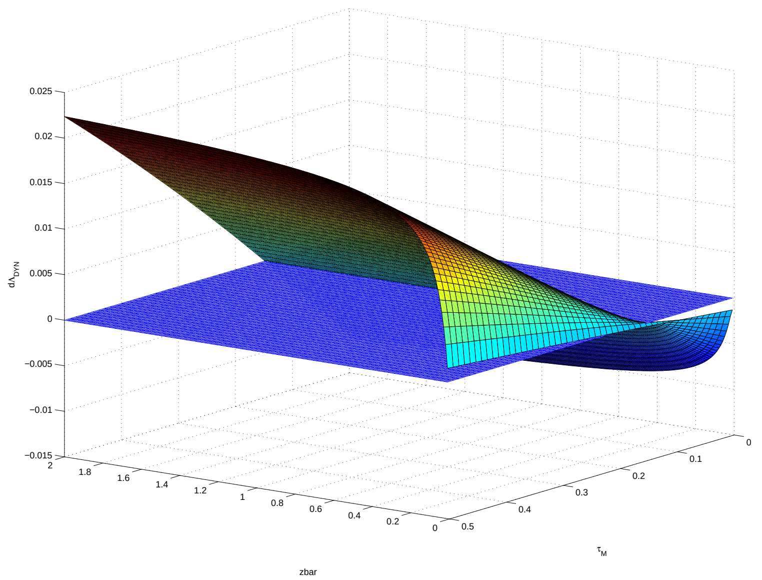
Notes: The other parameters are set at their benchmark values. The policy shock consists of $\tilde{\tau}_M = -0.01$, where $\tilde{t}_C$ is being determined endogenously to keep government revenue unchanged. Panels (c) and (d) can be found on the next page.

Figure 2.3: Welfare Effects of Coordinated Tax-Tariff Reform (continued)

(c) Different Pre-existing σ_{LL} and t_C



(d) Different Pre-existing $\bar{z}$ and τ_M



Notes: The other parameters are set at their benchmark values. The policy shock consists of $\tilde{\tau}_M = -0.01$, where $\tilde{t}_C$ is being determined endogenously to keep government revenue unchanged. Panel (d) exhibits the dynamic welfare effect, which is the total welfare effect net of the static part.

reveals that an increase in the pre-existing import tariff on capital goods has a negative effect on the welfare change. Intuitively, higher tariffs on imported capital goods decrease the size of the import-substitution sector and therefore counteract the effect of higher tariffs on imported consumption goods, which tend to increase the size of the import-substitution sector. Consequently, higher pre-existing tariffs on imported capital goods make pre-existing tariffs on imported consumption goods less harmful, leading to a smaller welfare gain of the cut in the import tariff rate on consumption goods. The welfare change turns negative at relatively high values of the pre-existing rates of the labor income tax and the import tariff on consumption goods.

Panel (c) of Figure 2.3 presents the reform's welfare implications for various values of the intertemporal elasticity of labor supply and initial consumption tax rates. In line with the results in Table 2.5, we find that the welfare change depends negatively on the labor supply elasticity. In addition, the negative relationship between the labor supply elasticity and the welfare change is stronger for higher pre-existing consumption tax rates. The figure shows that combinations of a relatively high pre-existing consumption tax rate and a relatively high intertemporal elasticity of labor supply may lead to a negative welfare effect.

Panel (d) of Figure 2.3 shows the dynamic welfare effect, which is obtained by subtracting the static welfare effect from the total welfare effect, for various values of the pre-existing import tariff rate on consumption goods and the mobility of physical capital, which is measured by $\bar{z}$. The absolute value of the dynamic welfare effect depends positively on capital mobility and converges to zero if capital mobility becomes low. The figure also shows a positive relationship between the pre-existing import tariff rate and the dynamic part of the welfare effect. The reason is that the import tariff positively affects the pre-reform steady-state stock of physical capital; the decrease in the capital stock brought about by the tax-tariff reform is more advantageous if the capital stock is further above (or to a smaller extent below) its second-best optimum. Furthermore, a higher mobility of physical capital increases the adjustment speed of the model, so that the discounted value of future utility changes becomes larger.

In summary, by finding a positive change in lifetime utility, our welfare analysis has shown that the coordinated tax-tariff reform moves the economy closer to its second best optimum starting from the benchmark calibration of a typical low-income country. The welfare effect depends crucially on the mix of pre-existing distortionary taxes and tariffs. Finally, by assuming exogenous labor supply and

Cobb-Douglas production functions one exaggerates the welfare effects of the reform, in particular the dynamic part of it.

2.6 Conclusions

We build a micro-founded macroeconomic model of a developing small open economy to study the dynamic welfare and allocation effects of revenue-neutral trade liberalization. In particular, we analyze a tax-tariff reform strategy of decreasing the tariff rate on imported consumption goods and simultaneously changing the domestic consumption tax rate in such a way that the path of government revenue remains unaffected. Our model features two production sectors, imperfect physical capital mobility, endogenous labor supply, and two different tax and two tariff instruments. We solve the model analytically and provide a simulation analysis to quantify the allocation effects of the reform and to determine the welfare change.

We find that the reform increases aggregate output in the short run, owing to a more efficient allocation of labor between the two production sectors and because of an increase in employment due to a wealth effect in labor supply. However, output and employment decrease in the long run, reflecting a fall in the physical capital stock. Output and employment in the import-substitution sector decrease, whereas output and employment in the export sector rise, more so in long run than in the short run. The gross volume of international trade (so-called market access), falls on impact and increases in the long run. Instantaneous utility recovers during the transition and, for a plausible calibration of the model, lifetime utility is shown to increase, which is induced by the net efficiency gain of the reform. The reason for the efficiency gain is that the reform alleviates the tariff distortion (resulting in too much production and too little consumption of import substitutes, and too much labor supply) more than it exacerbates the distortion of the consumption tax (giving rise to too little labor supply). Contrary to the static literature, we are able to distinguish between short-run and long-run effects on utility: because of the intertemporal reallocation of labor supply, instantaneous utility at the time of the shock goes down, causing the short-run welfare implications to differ from those found in the static literature. Moreover, we show that the incorporation of capital accumulation in the model leads to larger welfare effects than those obtained in static models.

The welfare effect depends crucially on the pre-existing tax and tariff rates. Furthermore, the endogeneity of labor supply, the elasticity of substitution between factors of production, and the degree of capital mobility affect the magnitude of the welfare change. Compared to exogenous labor supply, endogenous labor supply reduces the long-run welfare gain of the reform, because of the distortion of the household's intertemporal labor supply decision: in the short run, the wealth effect in labor supply puts upward pressure on the already sub-optimally large import-substitution sector. In terms of welfare losses, the harmfulness of the tariff rate on imported consumption goods increases with the size of the substitution elasticities between factors of production in both sectors so that imposing Cobb-Douglas production functions would lead to exaggerated welfare effects. Finally, a higher capital mobility amplifies the dynamic part of the welfare effect.

We have not addressed the political economy and intragenerational distribution aspects of tax-tariff reforms. Future research could try to fill this gap by introducing heterogeneity among households. In addition, to better capture the characteristics of developing countries, we would like to relax the assumption of perfect goods and factor markets. In the light of this, the next chapter investigates the effects of a coordinated tax-tariff reform if there exists a substantial shadow economy (i.e., the part of the economy that cannot be taxed by the government), which is often the case in developing countries.

2.A Appendix

This Appendix derives the quasi-reduced forms of the model conditional on the state variables (Section 2.A.1) and studies the dynamic system (Section 2.A.2).

2.A.1 Quasi-Reduced Forms

We express all endogenous variables of the model in terms of the state variables ($\tilde{K}$, $\tilde{q}$, $\tilde{X}$, $\tilde{F}$) and the tax policy instruments ($\tilde{t}_C$, $\tilde{\tau}_M$). In the following, we will drop time subscripts. We combine (T1.05)–(T1.07) to determine the labor market equilibrium:

$$\begin{bmatrix} \tilde{L} \\ \tilde{L}_M \\ \tilde{L}_E \\ \tilde{w} \end{bmatrix} = \begin{bmatrix} \omega_L & -\omega_L^M & -\omega_L^E & 0 \\ 0 & \frac{\theta_K}{\sigma_M} & 0 & 1 \\ 0 & 0 & \frac{\theta_Z}{\sigma_E} & 1 \\ 1 & 0 & 0 & -\sigma_{LL} \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ \frac{\theta_K}{\sigma_M}\tilde{K} + \tilde{\tau}_M \\ 0 \\ -\sigma_{LL}\tilde{X} \end{bmatrix}. \tag{A.2.1}$$

In single equation form, labor market equilibrium implies

$$\tilde{L} = \frac{\sigma_{LL}\theta_K\theta_Z\omega_L^M}{\sigma_E\sigma_M|\Omega|}\tilde{K} - \frac{\sigma_{LL}}{|\Omega|}\left(\frac{\theta_K\omega_L^E}{\sigma_M} + \frac{\theta_Z\omega_L^M}{\sigma_E}\right)\tilde{X} + \frac{\sigma_{LL}\theta_Z\omega_L^M}{\sigma_E|\Omega|}\tilde{\tau}_M, \tag{A.2.2}$$

$$\tilde{L}_M = \frac{\theta_K\left[\sigma_{LL}\theta_Z\omega_L + \sigma_E\omega_L^E\right]}{\sigma_M\sigma_E|\Omega|}\tilde{K} - \frac{\sigma_{LL}\theta_Z\omega_L}{\sigma_E|\Omega|}\tilde{X} + \frac{\sigma_{LL}\theta_Z\omega_L + \sigma_E\omega_L^E}{\sigma_E|\Omega|}\tilde{\tau}_M, \tag{A.2.3}$$

$$\tilde{L}_E = -\frac{\theta_K\omega_L^M}{\sigma_M|\Omega|}\tilde{K} - \frac{\sigma_{LL}\theta_K\omega_L}{\sigma_M|\Omega|}\tilde{X} - \frac{\omega_L^M}{|\Omega|}\tilde{\tau}_M, \tag{A.2.4}$$

$$\tilde{w} = \frac{\theta_K\theta_Z\omega_L^M}{\sigma_E\sigma_M|\Omega|}\tilde{K} + \frac{\sigma_{LL}\theta_K\theta_Z\omega_L}{\sigma_E\sigma_M|\Omega|}\tilde{X} + \frac{\theta_Z\omega_L^M}{\sigma_E|\Omega|}\tilde{\tau}_M, \tag{A.2.5}$$

where $|\Omega| \equiv \left[\theta_K(\sigma_{LL}\theta_Z\omega_L + \sigma_E\omega_L^E) + \sigma_M\theta_Z\omega_L^M\right](\sigma_M\sigma_E)^{-1} > 0$ denotes the absolute value of the determinant of the coefficient matrix on the right-hand side of (A.2.1).

By combining (T1.12)–(T1.15), we obtain quasi-reduced form expressions for consumption of both goods:

$$\tilde{C}_M = \frac{(\sigma_C - 1)\omega_C^M - \sigma_C\omega_C}{\omega_C}\tilde{\tau}_M - \tilde{t}_C + \tilde{X}, \tag{A.2.6}$$

$$\tilde{C}_E = (\sigma_C - 1)\frac{\omega_C^M}{\omega_C} - \tilde{t}_C + \tilde{X}. \tag{A.2.7}$$

The quasi-reduced form for government revenue is:

$$\tilde{T} = \xi_{TK}\tilde{K} + \xi_{TQ}\tilde{q} + \xi_{TX}\tilde{X} + \phi_{TC}\tilde{t}_C + \phi_{TM}\tilde{\tau}_M, \tag{A.2.8}$$

which is obtained by substituting (T1.09)–(T1.10), (A.2.2)–(A.2.3), and (A.2.5)–(A.2.7) into (T1.17), where the revenue elasticities for $\tilde{K}$, $\tilde{X}$, and $\tilde{q}$ are defined as:

$$\begin{aligned}
\xi_{TK} &\equiv \frac{t_L\omega_L\theta_K\theta_Z\omega_L^M(\sigma_{LL}+1)}{\sigma_E\sigma_M\,|\Omega|} - \frac{\tau_M\omega_L^M}{(1-\theta_K)(1+\tau_M)}\left[1-\frac{(1-\theta_K)\sigma_M\theta_Z\omega_L^M}{\sigma_E\sigma_M\,|\Omega|}\right] \\
&\quad + \frac{\tau_I}{1+\tau_I}\omega_I, \\
\xi_{TX} &\equiv \frac{t_L\omega_L\sigma_{LL}}{|\sigma_E\sigma_M\Omega|}\left(\theta_K\theta_Z\omega_L - \theta_K\omega_L^E\sigma_E - \theta_Z\omega_L^M\sigma_M\right) + \frac{t_C\omega_C^E}{1+t_C} \\
&\quad + \frac{t_C+\tau_M+t_C\tau_M}{(1+t_C)(1+\tau_M)}\omega_C^M + \frac{\tau_M}{1+\tau_M}\frac{\omega_L^M\sigma_{LL}\theta_Z\omega_L}{\sigma_E\,|\Omega|}, \\
\xi_{TQ} &\equiv \frac{\tau_I}{1+\tau_I}\frac{\omega_I}{\sigma_K},
\end{aligned}$$

and the revenue elasticities for the tax policy instruments are:

$$\begin{aligned}
\phi_{TC} &\equiv \frac{(1+\tau_M)\omega_C^E+\omega_C^M}{(1+\tau_M)(1+t_C)}, \\
\phi_{TM} &\equiv \frac{t_L\omega_L\theta_Z\omega_L^M}{\sigma_E\,|\Omega|}(1+\sigma_{LL}) + \frac{t_C+\tau_M+t_C\tau_M}{(1+t_C)(1+\tau_M)}\frac{(\sigma_C-1)\omega_C^M-\sigma_C\omega_C}{\omega_C}\omega_C^M \\
&+ \frac{t_C}{1+t_C}\frac{\omega_C^E\omega_C^M}{\omega_C}(\sigma_C-1) - \frac{\tau_M}{1+\tau_M}\omega_L^M\frac{\left[\sigma_{LL}\theta_Z\omega_L+\sigma_E\omega_L^E\right]}{\sigma_E\,|\Omega|} \\
&+ \left(\omega_C^M - \frac{1}{1-\theta_K}\omega_L^M\right).
\end{aligned}$$

By imposing $\tilde{T} = 0$, we obtain the endogenously determined time path of the consumption tax rate, which is given by (2.20) in the main text.

2.A.2 Dynamic System

2.A.2.1 Investment Subsystem

The investment system (2.21a) is obtained by substituting (T1.09)–(T1.10), and (A.2.3) into (T1.01)–(T1.02). The two non-zero elements in the Jacobian matrix Δ_I are:

$$\begin{aligned}
\delta_{KQ} &\equiv \frac{r\omega_I}{\chi_K\omega_K} > 0, \\
\delta_{QK} &\equiv \frac{r(\omega_L^M)^2\theta_K\theta_Z}{\sigma_E\sigma_M\omega_K\,|\Omega|} > 0,
\end{aligned}$$

and the non-zero shock terms in the matrix Λ_I are given by:

$$\lambda_{QX} \equiv \frac{r\omega_L^M \omega_L \sigma_{LL} \theta_K \theta_Z}{\sigma_E \sigma_M \omega_K |\Omega|} > 0,$$
$$\lambda_{QM} \equiv \frac{r\omega_L^M}{(1-\theta_K)\omega_K} \left[\frac{(1-\theta_K)\theta_Z \omega_L^M}{\sigma_E |\Omega|} - 1 \right] < 0.$$

The eigenvalues of Δ_I are given by:

$$-h_1^* = \frac{1}{2}\left(r - \sqrt{4\delta_{KQ}\delta_{QK} + r^2} \right) < 0, \tag{A.2.9}$$
$$r_1^* = \frac{1}{2}\left(r + \sqrt{4\delta_{KQ}\delta_{QK} + r^2} \right) = h_1^* + r > 0. \tag{A.2.10}$$

Hence, the model has one positive (unstable) eigenvalue and one negative (stable) eigenvalue, so that the steady state is unique and saddle point stable. Furthermore, we have

$$\lim_{\chi_K \to 0} \delta_{KQ} = \infty \Rightarrow \lim_{\chi_K \to 0} h_1^* = \infty, \tag{A.2.11}$$
$$\lim_{\chi_K \to \infty} \delta_{KQ} = 0 \Rightarrow \lim_{\chi_K \to \infty} h_1^* = 0. \tag{A.2.12}$$

This completes the proof of part (i) of Proposition 2.1.

We use the Laplace transform method as set out in Judd (1982) to derive impulse-response functions for the key variables of the system. The Laplace transform is defined as $\mathcal{L}\{x, s\} \equiv \int_0^\infty x(z)e^{-sz}dz$, where s denotes the discount rate and $\mathcal{L}$ is the Laplace transform operator. By taking the Laplace transform of (2.21a) and imposing $\tilde{K}(0) = 0$, we get:

$$\Gamma_I(s) \begin{bmatrix} \mathcal{L}\{\tilde{K}, s\} \\ \mathcal{L}\{\tilde{q}, s\} \end{bmatrix} = \Lambda_I \begin{bmatrix} \mathcal{L}\{\tilde{X}, s\} \\ \mathcal{L}\{\tilde{\tau}_M, s\} \end{bmatrix} + \begin{bmatrix} 0 \\ \tilde{q}(0) \end{bmatrix}, \tag{A.2.13}$$

where $\Gamma_I(s) \equiv sI - \Delta_I$ and I is the identity matrix. Multiplying both sides of (A.2.13) by $\Gamma_I(s)^{-1}$ yields:

$$(s+h_1^*) \begin{bmatrix} \mathcal{L}\{\tilde{K}, s\} \\ \mathcal{L}\{\tilde{q}, s\} \end{bmatrix} = \frac{\operatorname{adj}\Gamma_I(s)}{s - r_1^*} \begin{bmatrix} 0 \\ \tilde{q}(0) + \lambda_{QX}\mathcal{L}\{\tilde{X}, s\} + \lambda_{QM}\mathcal{L}\{\tilde{\tau}_M, s\} \end{bmatrix}, \tag{A.2.14}$$

where we used Cramer's rule to get:

$$\Gamma_I(s)^{-1} = \frac{\operatorname{adj}\Gamma_I(s)}{|\Gamma_I(s)|} = \frac{1}{(s - r_1^*)(s + h_1^*)} \operatorname{adj}\Gamma_I(s). \tag{A.2.15}$$

The adjoint matrix of $\Gamma_I(s)$ is given by:

$$\operatorname{adj}\Gamma_I(s) \equiv \begin{bmatrix} s-r & \delta_{KQ} \\ \delta_{QK} & s \end{bmatrix}. \tag{A.2.16}$$

Eliminating the positive root r_1^* that violates the transversality condition (2.14d) gives rise to the following condition:

$$\operatorname{adj}\Gamma_I(r_1^*) \begin{bmatrix} 0 \\ \tilde{q}(0) + \lambda_{QX}\mathcal{L}\{\tilde{X}, s\} + \lambda_{QM}\mathcal{L}\{\tilde{\tau}_M, s\} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \tag{A.2.17}$$

We investigate a one-off and permanent shock, so that $\tilde{\tau}_M(z) = \tilde{\tau}_M$ for all $z > 0$, which implies

$$\mathcal{L}\{\tilde{\tau}_M, s\} = \frac{\tilde{\tau}_M}{s}. \tag{A.2.18}$$

Furthermore, it follows from $r = \rho$ and (2.6b) that $\tilde{X}(z) = \tilde{X}(0)$ for all $z > 0$ so that

$$\mathcal{L}\{\tilde{X}, s\} = \frac{\tilde{X}(0)}{s}. \tag{A.2.19}$$

Therefore, condition (A.2.17) implies:

$$\tilde{q}(0) = -\frac{1}{r_1^*}\left(\lambda_{QX}\tilde{X}(0) + \lambda_{QM}\tilde{\tau}_M\right). \tag{A.2.20}$$

By substituting (A.2.20) into the first and second row of (A.2.14), we get

$$\mathcal{L}\{\tilde{K}, s\} = -\frac{1}{s(s+h_1^*)}\frac{\delta_{KQ}}{r_1^*}\left(\lambda_{QX}\tilde{X}(0) + \lambda_{QM}\tilde{\tau}_M\right), \tag{A.2.21}$$

$$\mathcal{L}\{\tilde{q}, s\} = -\frac{\lambda_{FQ}}{r_1^*}\frac{1}{s+h_1^*}\left(\lambda_{QX}\tilde{X}(0) + \lambda_{QM}\tilde{\tau}_M\right). \tag{A.2.22}$$

We take the inverse Laplace transform of (A.2.21) and (A.2.22) to obtain the impulse-response functions for Tobin's q and for the stock of physical capital:

$$\tilde{q}(z) = -\frac{1}{r+h_1^*}\left[\lambda_{QM}\tilde{\tau}_M + \delta_{QX}\tilde{X}(0)\right]e^{-h_1^* z}, \tag{A.2.23}$$

$$\tilde{K}(z) = \frac{\delta_{KQ}}{(r+h_1^*)h_1^*}\left[\lambda_{QM}\tilde{\tau}_M + \delta_{QX}\tilde{X}(0)\right]\left(1-e^{-h_1^* z}\right) = \frac{\delta_{KQ}}{h_1^*}\tilde{q}(0)\left(1-e^{-h_1^* z}\right), \tag{A.2.24}$$

so that the stable eigenvalue $-h_1^*$ determines the convergence speed of the investment system.

2.A.2.2 Savings Subsystem

The savings system (2.21b) is obtained by substituting (T1.09)–(T1.11), (A.2.3), (A.2.6), (A.2.7) into (T1.03). The elements in the matrix Δ_S are given by:

$$\delta_{FX} \equiv \frac{r\omega_L\sigma_{LL}\left[\sigma_E\sigma_M\left|\Omega\right|\frac{\varepsilon}{1-\varepsilon}(1-t_L)+\omega_L\theta_K\theta_Z t_L+(1-t_L)(\sigma_E\theta_K\omega_L^E+\sigma_M\theta_Z\omega_L^M)\right]}{-\sigma_E\sigma_M\left|\Omega\right|}<0,$$

$$\lambda_{FK} \equiv r\left[\frac{\omega_L^M}{1-\theta_K}\left(1-\frac{(1-\theta_K)\theta_Z\omega_L^M}{\sigma_E\left|\Omega\right|}\right)-\frac{\theta_K\omega_L^M\left[\omega_L^E\sigma_E+t_L\omega_L\theta_Z(\sigma_{LL}+1)\right]}{\sigma_E\sigma_M\left|\Omega\right|}-\omega_I\right],$$

and the elements of Λ_S are:

$$\lambda_{FQ} \equiv -\frac{r\omega_I}{\sigma_K}<0,$$

$$\lambda_{FM} \equiv \frac{r\left\{\left|\Omega\right|\sigma_E+(1-\theta_K)\left[\sigma_{LL}(1-t_L)-t_L\right]\theta_Z\omega_L\right\}\omega_L^M}{\sigma_E(1-\theta_K)\left|\Omega\right|}.$$

The eigenvalues of Δ_S are given by: $h_2^*=0$ and $r_2^*=r>0$. The zero root h_2^* implies that the savings system features a hysteretic steady state. Because there is exactly one strictly positive eigenvalue (r_2^*) and one forward-looking variable ($\tilde{X}$), the savings system is locally saddle point stable (Giavazzi and Wyplosz, 1985, p. 354). This proves part (ii) of Proposition 2.1.

We take the Laplace transform of (2.21b) and impose $\tilde{F}(0)=0$ to get:

$$\Gamma_S(s)\begin{bmatrix}\mathcal{L}\{\tilde{X},s\}\\ \mathcal{L}\{\tilde{F},s\}\end{bmatrix}=\Lambda_I\begin{bmatrix}\mathcal{L}\{\tilde{K},s\}\\ \mathcal{L}\{\tilde{q},s\}\\ \mathcal{L}\{\tilde{\tau}_M,s\}\end{bmatrix}+\begin{bmatrix}\tilde{X}(0)\\ 0\end{bmatrix}, \tag{A.2.25}$$

where $\Gamma_S(s)\equiv sI-\Delta_S$. Multiplying both sides of (A.2.25) by $\Gamma_S(s)^{-1}$ yields:

$$\begin{bmatrix}\mathcal{L}\{\tilde{X},s\}\\ \mathcal{L}\{\tilde{F},s\}\end{bmatrix}=\frac{\operatorname{adj}\Gamma_S(s)}{s(s-r)}\begin{bmatrix}\tilde{X}(0)\\ \lambda_{FK}\mathcal{L}\{\tilde{K},s\}+\lambda_{FQ}\mathcal{L}\{\tilde{q},s\}+\lambda_{FM}\mathcal{L}\{\tilde{\tau}_M,s\}\end{bmatrix}, \tag{A.2.26}$$

where we again used Cramer's rule to get:

$$\Gamma_S(s)^{-1}=\frac{\operatorname{adj}\Gamma_S(s)}{\left|\Gamma_S(s)\right|}=\frac{1}{s(s-r)}\operatorname{adj}\Gamma_S(s). \tag{A.2.27}$$

The adjoint matrix of $\Gamma_S(s)$ is given by:

$$\operatorname{adj}\Gamma_S(s)\equiv\begin{bmatrix}s-r & 0\\ \delta_{FX} & s\end{bmatrix}. \tag{A.2.28}$$

Eliminating the positive root r that violates transversality condition (2.14d) gives rise to the following condition:

$$\operatorname{adj}\Gamma_S(r)\begin{bmatrix}\tilde{X}(0)\\ \lambda_{FK}\mathcal{L}\{\tilde{K},r\}+\lambda_{FQ}\mathcal{L}\{\tilde{q},r\}+\lambda_{FM}\mathcal{L}\{\tilde{\tau}_M,r\}\end{bmatrix}=\begin{bmatrix}0\\0\end{bmatrix}. \quad \text{(A.2.29)}$$

By substituting (A.2.21) and (A.2.22) into the second row of (A.2.29) and using (A.2.18), we find:

$$-\left(\lambda_{FM}\tilde{\tau}_M+\delta_{FX}\tilde{X}(0)\right)=\frac{1}{r+h_1^*}\left[h_1^*\lambda_{FK}\tilde{K}(\infty)+r\lambda_{FQ}\tilde{q}(0)\right], \quad \text{(A.2.30)}$$

where $\tilde{q}(0)$ and $\tilde{K}(\infty)$ are obtained by evaluating (A.2.23) at $z=0$ and by taking the limit of (A.2.24) for $z\to\infty$, respectively. Together with (A.2.23) and (A.2.24), condition (A.2.30) can be solved for the jump in full consumption as a function of the change in the import tariff rate. The inverse Laplace transform of the first row of (A.2.26) gives:

$$\tilde{X}(z)=\tilde{X}(0), \quad \text{(A.2.31)}$$

which confirms the constancy of $\tilde{X}$ during the transition. We combine the second row of (A.2.26) with the second row of (A.2.29) to get:

$$\begin{aligned}\mathcal{L}\{\tilde{F},s\}=&\ \frac{\lambda_{FK}\delta_{KQ}}{r_1^*}\frac{1}{r}\left[\frac{1}{(s+h_1^*)(r+h_1^*)}+\frac{1}{s(s+h_1^*)}\right]\left(\lambda_{QX}\tilde{X}(0)+\lambda_{QM}\tilde{\tau}_M\right)\\&+\frac{\lambda_{FQ}}{r_1^*}\frac{1}{(s+h_2^*)(r+h_2^*)}\left(\lambda_{QX}\tilde{X}(0)+\lambda_{QM}\tilde{\tau}_M\right)\\&+\frac{1}{sr}\left(\delta_{FX}\tilde{X}(0)+\lambda_{FM}\tilde{\tau}_M\right). \end{aligned}\quad \text{(A.2.32)}$$

By taking the inverse Laplace transform of (A.2.32) and using (A.2.23) and (A.2.24), we obtain the impulse-response function for the stock of net foreign assets:

$$\begin{aligned}\tilde{F}(z)=&\ -\left[\left(\frac{1}{r}-\frac{e^{-h_1^*z}}{r+h_1^*}\right)\lambda_{FK}\tilde{K}(\infty)+\frac{e^{-h_1^*z}}{r+h_1^*}\lambda_{FQ}\tilde{q}(0)\right]\\&-\frac{1}{r}\left(\lambda_{FM}\tilde{\tau}_M+\delta_{FX}\tilde{X}(0)\right).\end{aligned}\quad \text{(A.2.33)}$$

2.A.2.3 Value of Land

By substituting (T1.08) and (A.2.4) into (T1.04), we find the quasi-reduced form differential equation for the value of land:

$$\dot{\tilde{V}}_Z=r\tilde{V}_Z+\lambda_{ZK}\tilde{K}+\lambda_{ZX}\tilde{X}+\lambda_{ZM}\tilde{\tau}_M, \quad \text{(A.2.34)}$$

with

$$\lambda_{ZK} \equiv \frac{r\omega_Z(1-\theta_Z)\theta_K\omega_L^M}{\sigma_E\sigma_M\,|\Omega|} > 0, \tag{A.2.35}$$

$$\lambda_{ZX} \equiv \frac{r\omega_Z(1-\theta_Z)\sigma_{LL}\theta_K\omega_L}{\sigma_E\sigma_M\,|\Omega|} > 0, \tag{A.2.36}$$

$$\lambda_{ZM} \equiv \frac{r\omega_Z(1-\theta_Z)\omega_L^M}{\sigma_E\,|\Omega|} > 0. \tag{A.2.37}$$

The Laplace transform of (A.2.34) is given by:

$$(s-r)\mathcal{L}\{\tilde{V}_Z, s\} = \tilde{V}_Z(0)+\lambda_{ZK}\mathcal{L}\{\tilde{K}, s\}+\lambda_{ZK}+\mathcal{L}\{\tilde{X}, s\}+\lambda_{ZM}\mathcal{L}\{\tilde{\tau}_M, s\}. \tag{A.2.38}$$

We substitute the Laplace transforms (A.2.18), (A.2.19), and (A.2.21) into (A.2.38) to obtain:

$$\begin{aligned}(s-r)\mathcal{L}\{\tilde{V}_Z, s\} = {} & \tilde{V}_Z(0) - \frac{\lambda_{ZK}\delta_{KQ}}{r_1^* s(s+h_1^*)}\left(\lambda_{QX}\tilde{X}(0)+\lambda_{QM}\tilde{\tau}_M\right) + \frac{\lambda_{ZX}}{s}\tilde{X}(0) \\ & + \frac{\lambda_{ZM}}{s}\tilde{\tau}_M. \end{aligned} \tag{A.2.39}$$

Eliminating the unstable root r, we find the following condition for the jump in the value of land:

$$\tilde{V}_Z(0) = \frac{\lambda_{ZK}\delta_{KQ}}{r_1^* r(r+h_1^*)}\left(\lambda_{QX}\tilde{X}(0)+\lambda_{QM}\tilde{\tau}_M\right) - \frac{1}{r}\left(\lambda_{ZX}\tilde{X}(0)+\lambda_{ZM}\tilde{\tau}_M\right). \tag{A.2.40}$$

Using (A.2.24) and combining (A.2.39) and (A.2.40), we obtain the impulse-response function for the value of land:

$$\tilde{V}_Z(z) = -\lambda_{ZK}\frac{h_1^*}{r+h_1^*}\tilde{K}(\infty)\left[\frac{1}{h_1^*}(1-e^{-h_1^* z})+\frac{1}{r}\right] \tag{A.2.41}$$

$$-\frac{1}{r}\left(\lambda_{ZX}\tilde{X}(0)+\lambda_{ZM}\tilde{\tau}_M\right). \tag{A.2.42}$$

2.A.2.4 Utility Price Index

In order to derive (2.27) in the main text, we use the time path of the price index of utility

$$\tilde{p}_U(z) = \tilde{p}_U(\tau)e^{-h_2^*(z-\tau)} + \tilde{p}_U(\infty)\left(1-e^{-h_2^*(z-\tau)}\right), \quad z \geqslant \tau, \tag{A.2.43}$$

which is obtained by substituting (A.2.5), (A.2.24), and (T1.14)–(T1.15) into (T1.18).

Chapter 3

Coordinated Tax-Tariff Reforms and the Shadow Economy

"Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."

— Winston Churchill (1874-1965)

3.1 Introduction

Tariff revenue of low-income countries has declined from 5.4 percent of GDP in 1985 to 3 percent of GDP in 2010, which is primarily driven by their trade liberalization programs. Nevertheless, trade taxes continue to be the major source of revenue for these nations: tariff revenue accounted on average for 29 percent of total tax revenue during 2000–2010 compared with only 1 percent in OECD countries.[1] The strong dependence on trade tax revenues may impede further liberalization of trade in low-income countries. Therefore, Washington-based financial institutions such as the International Monetary Fund (IMF) and the World Bank have strongly advocated tariff cuts coupled with tax measures to recoup the potential public revenue losses. Much of the discussion on alternative revenue sources has focused on consumption taxes like the value-added tax (VAT). Policy prescriptions of the IMF and the World Bank are typically based on the (presumed) efficiency gain of these integrated tax-tariff reforms.[2] Recently, Emran

[1] See Ebrill et al. (1999) and World Bank (2012). Income groups are defined by the World Bank classification.

[2] The basic rationale for this gain goes back to Diamond and Mirrlees (1971), who show that it is desirable to have zero tariffs on all goods if all taxes would be set at the optimal level.

and Stiglitz (2005) have challenged the validity of this prescription by pointing to the efficiency loss induced by the presence of a 'hard-to-tax' informal sector, which is often of substantial size in developing countries.[3] Our chapter contributes to this debate. More specifically, we show that the Washington-based policy line remains valid under plausible conditions—even when a substantial informal sector exists—once allowance is made for factor market dynamics.

There is a large informal literature discussing potential measures to offset the revenue loss of tariff reform. See, for example, Mitra (1999). Early theoretical contributions are those by Hatzipanayotou et al. (1994) and Keen and Ligthart (2002), who study the revenue and welfare effects of tariff cuts accompanied by a one-for-one increase in consumption tax rates. They find that these integrated tax-tariff reforms increase both government revenue and welfare. Intuitively, the reform reduces the *implicit* production subsidy at an unchanged consumption tax distortion. Recently, the desirability of integrated reform strategies has been under discussion. The main result may break down when allowance is made for important features of reality such as imperfect competition on the goods market (cf. Haque and Mukherjee, 2005; and Keen and Ligthart, 2005) and tax administration costs (cf. Munk, 2008). Furthermore, Anderson and Neary (2007) and Kreickemeier and Raimondos-Møller (2008) show that welfare-improving integrated tax-tariff reforms do not necessarily increase the volume of international trade.

Our work is most closely related to Emran and Stiglitz (2005), who show that the welfare gain of integrated tax-tariff reforms also may vanish if allowance is made for the incomplete coverage of VAT owing to the existence of an informal sector. Employing a static model with fixed factor endowments, Emran and Stiglitz (2005) investigate the welfare effect of an integrated tax-tariff reform so as to leave government revenue unchanged. While a radial tariff reduction is shown to alleviate both consumption and production distortions, the revenue-neutral increase in the VAT reinforces the consumption distortion across formal and informal sectors.[4] As a result, they find that such a reform reduces welfare under plausible

[3]Schneider and Enste (2000) report informal sector sizes varying from 13 to 76 percent of Gross Domestic Product (GDP) for developing countries. Following Schneider and Enste (2000), the informal sector includes "unreported income from the production of legal goods and services, either from monetary or barter transactions." Throughout the chapter, we use the terms home production, informal sector, and shadow economy interchangeably.

[4]Emran and Stiglitz's (2005) analysis concerns the case of a selective tax-tariff reform, which contrary to a radial reform only applies to a subset of the commodities subject to the tax and the tariff. However, they claim that the results go through for a radial reform, which they work out in an (unpublished) paper.

conditions. Keen (2008) argues that Emran and Stiglitz (2005) underestimate the extent to which the VAT is able to tax the informal sector, because the VAT functions as a tax on the purchases (including imports) of firms in the informal sector. Furthermore, Davies and Paz (2011) find a welfare gain despite the existence of an informal sector, because of a selection effect generated by heterogeneous firms. In their model, firms with a relatively low productivity endogenously choose to operate in the informal sector. As a result, tariff cuts decrease the informal sector size, because they drive the least productive firms out of the market.

In our analysis, we abstract from the mechanisms put forward in these latter two papers, and instead focus on another aspect: although Emran and Stiglitz (2005) take into account the static output distortion induced by the import tariff, their model ignores the dynamic distortion of the tariff. In a dynamic setting, import tariff cuts reduce investment by firms and thereby depress the physical capital stock. Given that import-competing sectors are typically much more capital intensive than the rest of the economy (including the informal sector), the import tariff is more distorting compared to the consumption tax than it is in a static analysis. Emran and Stiglitz (2005) are not the only ones that ignore dynamic effects: in general, the existing literature typically employs static (partial) equilibrium frameworks to analyze piecemeal tax-tariff reforms and thus can neither take into account important effects on domestic factor markets nor consider transitional dynamics. Some notable exceptions are Naito (2006a; 2006b), who studies coordinated tax-tariff reforms in endogenous growth frameworks. His work, however, ignores the existence of an informal sector.

Our work extends the literature by explicitly considering an informal sector and dynamic effects. In so doing, we contribute to the academic literature as well as to the policy discussion about the desirability of integrated tax-tariff reforms in developing countries. To this end, we construct a model of a small open developing economy that we use to study the revenue, efficiency, and intergenerational welfare effects of a reform strategy of cutting tariffs and increasing destination-based consumption taxes so as to leave domestic consumer price index unchanged. Besides being analytically simple, the strategy of keeping consumer prices fixed is also practical. Compared with a revenue-neutral reform—which requires an analysis of time-varying consumption tax rates—all that is needed is information on the current marginal tariff, tax rates, and the expenditure share on imported consumption goods.

We consider a model in which households are finitely lived, building on the work of Yaari (1965) and Blanchard (1985). The Blanchard-Yaari overlapping generations specification not only describes the household sector more realistically than infinite-horizon models, but also provides a useful instrument to 'close' small open economy models.[5] In line with the economic structure of a typical developing country, households engage in home production (cf. Schneider, 2002, p. 30). Because of measurement problems, this kind of informal output neither enters the national accounts nor can be taxed (cf. Tanzi, 1999). The home production specification builds on the real business cycle (RBC) literature (cf. Benhabib et al., 1991; Parente et al., 2000; and Campbell and Ludvigson, 2001). In our framework, firms operate in two market sectors, that is, an export sector and an import-substitution sector. Following Brock and Turnovsky (1993), the export sector produces an agricultural good using labor and a sector-specific factor (land), whereas the import-substitution sector produces a manufactured good employing labor and imported physical capital as a sector-specific factor. In line with the static tax-tariff reform literature, we abstract from labor market frictions, which are typical of developing countries. The goods and factor markets are perfectly competitive. Financial capital is perfectly mobile. However, to avoid an unrealistically high mobility of physical capital, capital accumulation is subject to adjustment costs.

We solve the model analytically and provide numerical illustrations of the transitional allocation dynamics and the welfare effects of a tax-tariff reform. To this latter end, we simulate the model for empirically plausible parameter values. The reform strategy is shown to increase government revenue and market access in the long run, because steady-state imports and exports both rise. In addition, both the informal and formal agricultural sector expand at the expense of the import-substitution sector; however, informal agricultural output rises relatively more. Aggregate formal employment and output fall, more so in the long run than in the short run. The qualitative allocation effects are robust to changes in the size of the informal sector. In spite of the existence of a substantial informal sector, we find an efficiency gain under plausible conditions. Intuitively, the reform alleviates the tariff distortion (yielding too much production and too little consumption

[5]The infinite-horizon model of a small open economy yields a hysteretic steady state. The intergenerational externality that is present in the finite-horizon model induces an endogenously determined (non-hysteretic) steady state (cf. Schmitt-Grohe and Uribe, 2003; and Heijdra and Ligthart, 2010).

of import substitutes) more than it exacerbates the consumption tax distortion (giving rise to excess home production). More specifically, in addition to a static efficiency gain, lower tariff rates also generate an intertemporal efficiency gain; that is, tariff cuts reduce the larger than socially optimal physical capital stock in the import-substitution sector. The welfare change is unequally distributed across generations. Old existing generations benefit more than young generations. Future generations may even become worse off, depending on the pre-existing tax and tariff rates and the share of informal output in GDP.

The chapter proceeds as follows. Section 2 sets out a micro-founded model of a small open economy extended with an informal sector. Section 3 describes the solution procedure. Section 4 studies the dynamic allocation effects of a consumer-price neutral tax-tariff reform strategy in which tariffs on imported consumption goods are lowered and destination-based consumption taxes are increased. Section 5 studies the dynamic efficiency and intergenerational welfare effects. Section 6 concludes.

3.2 The Model

This section sets out the dynamic micro-founded model of a small open developing country. We subsequently discuss behavior of individual households, aggregate households, firms, and the government.

3.2.1 Individual Households

Following Yaari (1965) and Blanchard (1985), individual households face a constant probability of death $\beta \geqslant 0$, which equals the rate at which new agents are born. Consequently, the population size is constant and can thus be normalized to unity. Households are disconnected and therefore do not leave bequests. Actuarially fair annuity markets allow households to borrow and lend funds at the exogenously given world rate of interest adjusted for the probability of death.[6]

Expected lifetime utility at time t of a representative household born at time $v \leqslant t$ is given by the following additively separable specification:

$$\Lambda(v,t) = \int_t^{\infty} \ln C(v,z) e^{-(\rho+\beta)(z-t)} dz, \tag{3.1}$$

[6] The introduction of imperfections in the annuity market, in the spirit of Heijdra and Mierau (2012), does not change our results qualitatively. Details are available from the authors upon request.

where ρ is the pure rate of time preference. Consumption is discounted at the effective discount rate $\rho+\beta$, reflecting the death rate. The aggregate consumption index $C(v,t)$ is given by:

$$C(v,t) \equiv C_M(v,t)^{\varepsilon} C_A(v,t)^{1-\varepsilon}, \qquad 0 < \varepsilon < 1,$$

which is defined over a manufactured good $C_M(v,t)$ and a composite agricultural good $C_A(v,t)$. The parameter ε represents the consumption share of manufactured goods. Households can either choose to buy $C_E(v,t)$ agricultural goods on the market or produce $C_S(v,t)$ of these goods at home:[7]

$$C_A(v,t) \equiv C_E(v,t) + C_S(v,t).$$

The household allocates its total time available, which we have normalized to unity, between working $L_F(v,t)$ hours in the market sector and working $L_S(v,t)$ hours at home (so-called informal employment). The household's home production function is given by:

$$C_S(v,t) = Y_S(v,t) = \Omega_S L_S(v,t)^{1-\alpha_S}, \qquad 0 < \alpha_S < 1, \;\; \Omega_S > 0, \tag{3.2}$$

where Ω_S is a productivity index, $Y_S(v,t)$ is home production, and $1-\alpha_S$ is the output elasticity of time devoted to home production. Equation (3.2) says that home production of generation v is fully consumed by the representative household of that generation. All *implicit* income earned in the informal sector is attributed to labor.

The household's flow budget constraint is:

$$\begin{aligned}\dot{A}(v,t) = {} & (r+\beta)A(v,t) + w(t)L_F(v,t) + T(t) \\ & - p_M(t)C_M(v,t) - p_E(t)C_E(v,t),\end{aligned} \tag{3.3}$$

where $\dot{A}(v,t) \equiv dA(v,t)/dt$, $A(v,t)$ denotes financial wealth, r is the world rate of interest, $w(t)$ is the wage rate, $L_F(v,t)$ is total employment in the market sector, $T(t)$ are age-independent lump-sum transfers, $p_M(t)$ is the domestic consumer price of manufactured goods, and $p_E(t)$ is the domestic consumer price of agricultural goods produced in the export sector. The world market prices of agricultural and manufactured goods are exogenously given. Hence, we can normalize them

[7] This specification is warranted because home and market goods are typically close substitutes in developing countries (Parente et al., 2000, p. 683).

to unity. The domestic consumer prices of manufactured and agricultural goods produced in the market are defined as:

$$p_M(t) \equiv (1 + t_C(t))(1 + \tau_M(t)), \qquad p_E(t) \equiv 1 + t_C(t),$$

where $\tau_M(t)$ is an ad valorem import tariff on imported manufactured goods and $t_C(t)$ denotes an ad valorem destination-based consumption tax (which is applied to the tariff-inclusive import price, as is customary). In line with IMF policy advice (cf. IMF, 2011) and 53 percent of existing VAT systems (cf. Ebrill et al., 2001), a single tax rate applies to both consumption goods. Having only a single rate of VAT considerably reduces tax administration costs, which is important for developing countries with typically weak administrative capacities (cf. Munk, 2008).

The representative household of cohort v chooses time profiles for $C_M(v,t)$, $C_E(v,t)$, and $C_S(v,t)$ to maximize $\Lambda(v,t)$ subject to its flow budget constraint (3.3), the home production function (3.2), and a No-Ponzi-Game solvency condition. By solving this optimization problem, we find the following three necessary conditions:

$$\frac{\varepsilon}{1-\varepsilon}\frac{C_A(v,t)}{C_M(v,t)} = \frac{p_M(t)}{p_A(t)}, \tag{3.4a}$$

$$p_A(t)(1-\alpha_S)\Omega_S L_S(v,t)^{-\alpha_S} = w(t), \tag{3.4b}$$

$$\frac{\dot{X}(v,t)}{X(v,t)} = r - \rho, \tag{3.4c}$$

where $p_A(t)$ is the price index of composite agricultural consumption and *full* consumption $X(v,t)$ is defined as the market value of aggregate consumption:

$$X(v,t) \equiv p_C(t)C(v,t) = p_M(t)C_M(v,t) + p_A(t)C_A(v,t), \tag{3.5}$$

where $p_C(t)$ is the *true* price index of the aggregate consumption index:

$$p_C(t) = \Phi_C p_M(t)^{\varepsilon} p_A(t)^{1-\varepsilon}, \qquad \Phi_C \equiv \left[\varepsilon^{\varepsilon}(1-\varepsilon)^{1-\varepsilon}\right]^{-1} > 0.$$

Because $C_E(v,t)$ and $C_S(v,t)$ are perfect substitutes, the shadow price of home production $p_S(t)$ equals that of the agricultural good produced in the market: $p_S(t) = p_E(t) = p_A(t)$. Condition (3.4a) sets the marginal rate of substitution between agricultural goods and imported goods equal to their relative price. Equation (3.4b) says that the value of the marginal product of time devoted to informal activities should be equal to the market wage rate. According to (3.4c), optimal individual full consumption growth is given by the difference between the interest rate and the pure rate of time preference. We consider the case of a patient nation for which $r > \rho$ holds.[8] By integrating (3.3), and using (3.4c) and (3.5), it follows that full consumption of the representative household is a fixed fraction of total wealth:

$$X(v,t) = (\rho + \beta)\left[A(v,t) + H(v,t)\right], \tag{3.6}$$

where $H(v,t)$ is human capital of vintage v at time t:

$$H(v,t) \equiv \int_t^{\infty} \left[w(z)L_F(v,z) + T(z) + p_S(z)Y_S(v,z)\right] e^{-(r+\beta)(z-t)} dz,$$

which equals the expected discounted value of the current and future returns to labor, consisting of formal wage income, lump-sum transfers, and all implicit income earned in the shadow economy.

3.2.2 Aggregate Household Sector

Aggregate variables can be calculated from the individual variables by integrating over all existing generations while noting that in each period the number of newborns β is equal to the number of households that pass away. We assume large cohorts, so that frequencies and probabilities coincide by the law of large numbers. Therefore, aggregate full consumption, for example, is given by:

$$X(t) \equiv \int_{-\infty}^{t} \beta X(v,t) e^{\beta(v-t)} dv. \tag{3.7}$$

The aggregate values for other variables can be derived in a similar fashion. By taking the time derivative of (3.7), the aggregate version of (3.4c) is obtained:

$$\frac{\dot{X}(t)}{X(t)} = r - \rho - \beta(\rho+\beta)\frac{A(t)}{X(t)} = \frac{\dot{X}(v,t)}{X(v,t)} - \beta\frac{X(t) - X(t,t)}{X(t)}. \tag{3.8}$$

Aggregate full consumption growth differs from individual full consumption growth because of the generational turnover effect (cf. Heijdra and Ligthart, 2010). On the one hand, the birth of new generations has a positive effect on aggregate consumption growth (represented by the term $\beta X(t,t)$ on the right-hand side of the second equality sign). On the other hand, the death of old generations

[8] In this case, net foreign assets are strictly positive in the initial steady state.

has a negative effect on aggregate growth, reflecting that they cease to consume (represented by the term $-\beta X(t)$). Because old generations are wealthier than newborn households, they consume more. Consequently, on balance, aggregate full consumption growth falls short of individual full consumption growth.

Aggregate informal output is given by:

$$Y_S(t) = \int_{-\infty}^{t} \beta Y_S(v,t) e^{\beta(v-t)} dv. \tag{3.9}$$

Because the real wage rate is the same for every generation, it follows from (3.4b) that the level of individual informal production is independent of the household's age. Hence, we know that individual informal production and aggregate informal production coincide: $Y_S(t) = Y_S(v,t)$.[9]

3.2.3 Firms

Production of market goods takes place in an agricultural sector and a manufacturing sector. Formal agricultural firms produce predominantly for the export market, but also sell products on the domestic market. Domestic manufacturing firms compete with foreign firms that produce a perfect substitute for the manufactured commodity. Both sectors are perfectly competitive, yielding zero excess profits.

3.2.3.1 Export Sector

Output in the export sector $Y_E(t)$ is produced according to the following Cobb-Douglas production function:

$$Y_E(t) = \Omega_E Z_E^{\alpha_E} L_E(t)^{1-\alpha_E}, \qquad 0 < \alpha_E < 1, \;\; \Omega_E > 0, \tag{3.10}$$

where Ω_E is a productivity index, Z_E denotes the fixed factor land, $L_E(t)$ is employment in the export sector, and α_E is the output elasticity of land. The representative firm in the export sector maximizes its net operating surplus:

$$\Pi_E(t) \equiv Y_E(t) - w(t)L_E(t) - r_Z(t)Z_E,$$

where $r_Z(t)$ is the rental rate on land. We assume that the government is not able to tax rents on land, because of the lack of clear property rights in developing countries (cf. De Soto, 2001).

[9] Aggregate variables and variables averaged over all generations are equal, because of the normalization of the population size to unity.

The first-order conditions characterizing the firm's optimal plans are

$$w(t) = (1-\alpha_E)\Omega_E \left(\frac{Z_E}{L_E(t)}\right)^{\alpha_E}, \qquad r_Z(t) = \alpha_E \Omega_E \left(\frac{Z_E}{L_E(t)}\right)^{-(1-\alpha_E)}. \quad (3.11)$$

These expressions represent the exporter's demand functions for labor and land, respectively.

3.2.3.2 Import-Substitution Sector

The representative firm in the import-substitution sector produces $Y_M(t)$ according to a Cobb-Douglas technology:

$$Y_M(t) = \Omega_M K(t)^{\alpha_M} L_M(t)^{1-\alpha_M}, \qquad 0 < \alpha_M < 1, \;\; \Omega_M > 0, \quad (3.12)$$

where Ω_M is a productivity index, $L_M(t)$ is employment in the import-substitution sector, $K(t)$ denotes the physical capital stock, and α_M is the output elasticity of physical capital in the manufacturing sector. Capital goods can only be imported, do not bear any tariff or tax, and are subject to adjustment costs. We use capital goods as numeraire so that the world market price of capital goods is normalized to unity (i.e., $p_I = 1$). Following Uzawa (1969), the firm faces a strictly concave accumulation function $\Psi(\cdot)$ that links net capital accumulation to gross investment:

$$\dot{K}(t) = \left[\Psi\left(\frac{I(t)}{K(t)}\right) - \delta\right] K(t), \quad (3.13)$$

where $\delta > 0$ is the constant rate of capital depreciation and $I(t)$ denotes gross investment. The accumulation function has the following properties: $\Psi(0) = 0$, $\Psi'(\cdot) > 0$, and $\Psi''(\cdot) < 0$. Because of adjustment costs, physical capital is less mobile in the short run than in the long run. The degree of physical capital immobility is given by $\chi_K \equiv -(I/K)\Psi''/\Psi' > 0$, where a small χ_K characterizes a high degree of capital mobility. Note that the limiting cases of $\chi_K \to 0$ and $\chi_K \to \infty$ correspond to perfect and no capital mobility, respectively.

The firm chooses employment and investment to maximize the net present value of its cash flows,

$$V_K(t) \equiv \int_t^{\infty} \left[(1+\tau_M(z))Y_M(z) - w(z)L_M(z) - I(z)\right] e^{-r(z-t)} dz,$$

subject to the production function (3.12), the accumulation equation (3.13), and a transversality condition: $\lim_{z\to\infty} q(z)K(z)e^{-r(z-t)} = 0$, where $q(t)$ denotes Tobin's

q, which measures the market value of physical capital relative to its replacement costs. The firm takes the (positive) initial stock of physical capital as given. The optimization procedure yields the following first-order conditions:

$$w(t) = (1+\tau_M(t))(1-\alpha_M)\Omega_M\left(\frac{K(t)}{L_M(t)}\right)^{\alpha_M}, \tag{3.14a}$$

$$1 = q(t)\Psi'\left(\frac{I(t)}{K(t)}\right), \tag{3.14b}$$

$$\frac{\dot{q}(t) + (1+\tau_M(t))\alpha_M\frac{Y_M(t)}{K(t)}}{q(t)} = r + \delta - \left[\Psi\left(\frac{I(t)}{K(t)}\right) - \Psi'\left(\frac{I(t)}{K(t)}\right)\frac{I(t)}{K(t)}\right]. \tag{3.14c}$$

Equation (3.14a) yields labor demand conditional on the physical capital stock. Investment demand is given by (3.14b), which is a positive function of Tobin's q. Equation (3.14c) describes the evolution of Tobin's q, which ensures that the return on physical capital (the left-hand side) equals the user costs of physical capital (the right-hand side). The return on physical capital is the sum of the shadow capital gains/losses and the marginal product of capital. The user costs of physical capital consist of the interest rate, the depreciation rate, and the term between brackets, which captures the effect of investment on future adjustment costs. Because the adjustment function is strictly concave, the bracketed term is positive. Intuitively, current investment increases the future capital stock, thereby lowering future adjustment costs.[10]

3.2.4 Government

The government levies taxes on consumption in the formal sector, but cannot tax consumption of informal goods.[11] In addition, the government imposes tariffs on imported consumption goods. In line with international practice, all consumption taxes are destination-based, implying that exported goods are zero-rated and imported goods are taxed. The government distributes tax revenues to households in a lump-sum fashion. Hence, the government's budget identity is given by:

$$T(t) = t_C(t)\left[C_E(t) + (1+\tau_M(t))C_M(t)\right] + \tau_M(t)[C_M(t) - Y_M(t)]. \tag{3.15}$$

[10] Without adjustment costs, we have $\Psi(\cdot) = I(t)/K(t)$, which yields $\chi_K = 0$. Equation (3.14b) then reduces to $q(t) = 1$. In this case, $q(t)$ and $K(t)$ adjust instantaneously to their steady-state levels. Consequently, equation (3.14c) collapses to $(1+\tau_M)\frac{\partial Y_M}{\partial K} = r + \delta$, which is the familiar rental rate derived in a static framework.

[11] Tax evasion in the informal sector is assumed to be 100 percent. We thus abstract from the possibility of tax audits as in Turnovsky and Basher (2009).

The first term on the right-hand side of (3.15) represents consumption tax revenue, where we take into consideration that consumption taxes are levied on the domestic consumption of $C_E(t)$ and the tariff-inclusive value of $C_M(t)$. The second term denotes tariff revenue from imported consumption goods.

3.2.5 Macroeconomic Equilibrium

Given the relative market prices, there is a domestic excess demand for the manufacturing good and a domestic excess supply of the agricultural good. Imports of the manufacturing good are equal to $X_M(t) \equiv C_M(t) - Y_M(t)$ and exports of the agricultural good amount to $X_M(t) \equiv Y_E(t) - C_E(t)$. Subtracting investment from net exports and adding the return to net foreign assets, we obtain the change of net foreign assets F, given by the current account of the balance of payments:

$$\dot{F}(t) = rF(t) + Y_E(z) + Y_M(z) - C_E(z) - C_M(z) - I(z).$$

National solvency is retained provided the initial value of net foreign assets equals the present value of trade account deficits:

$$F(t) = -\int_t^{\infty} \left[Y_E(z) + Y_M(z) - C_E(z) - C_M(z) - I(z)\right] e^{-r(z-t)} dz.$$

Financial market equilibrium implies that household's aggregate claim on assets equals the sum of the value of the domestic physical capital stock $V_K(t)$, the value of the stock of land $V_Z(t)$, and net foreign assets:

$$A(t) = V_K(t) + V_Z(t) + F(t).$$

The stock market value of import-competing firms is given by $V_K(t) \equiv q(t)K(t)$. All financial assets are assumed to be perfect substitutes. Arbitrage ensures that land attracts the market rate of return, which consists of the sum of the capital gain $\dot{V}_Z(t)$ and the rental rate $r_Z(t)$:

$$rV_Z(t) = \dot{V}_Z(t) + r_Z(t)Z_E.$$

Labor market equilibrium requires that $L_F(t) + L_S(t) = 1$, where aggregate formal employment is $L_F(t) = L_E(t) + L_M(t)$ and aggregate informal employment is $L_S(t)$. Labor is perfectly mobile across the informal and formal sector and within the formal sector. We define the country's Gross Domestic Product (valued at domestic market prices) as: $Y(t) = (1 + t_C(t))[(1 + \tau_M(t))Y_M(t) + Y_E(t)]$. In line with international practice, official GDP does not include any output produced in the informal economy.

3.3 Solving the Model

This section solves the model, describes its dynamic properties, and discusses the parameters used in the numerical simulations of Sections 4 and 5.

3.3.1 Steady State

To analyze the dynamic properties of the model, we log-linearize it around an initial steady state (Table 3.1).[12] Tildes ($\tilde{}$) denote relative changes from the initial steady state for most variables (e.g., $\tilde{X}(t) \equiv dX(t)/X$), where X denotes the initial steady-state value of full consumption. Exceptions are financial variables and human wealth, which are scaled by output (e.g., $\tilde{A}(t) \equiv r dA(t)/Y$), lump-sum transfers ($\tilde{T}(t) \equiv dT(t)/Y$), and tax and tariff rates ($\tilde{t}_C(t) \equiv dt_C(t)/(1 + t_C)$ and $\tilde{\tau}_M(t) \equiv d\tau_M(t)/(1 + \tau_M)$). Time derivatives of variables are generally defined as $\dot{\tilde{X}}(t) \equiv d\dot{X}(t)/X$, except for the time derivative of financial wealth and human capital, which are scaled by output (e.g., $\dot{\tilde{A}}(t) \equiv r d\dot{A}(t)/Y$). See Appendix 3.A.1 for a further discussion. The model can be reduced to a four dimensional dynamic system, which consists of two predetermined variables $[\tilde{K}(t), \tilde{A}(t)]$ and two non-predetermined or forward-looking variables $[\tilde{q}(t), \tilde{X}(t)]$.[13] The investment subsystem $[\tilde{q}(t), \tilde{K}(t)]$ can be solved independent of the savings subsystem $[\tilde{X}(t), \tilde{A}(t)]$. Proposition 3.1 summarizes the stability properties of the model.

Proposition 3.1. *The model is locally saddle-point stable if* $r < \rho + \eta\beta$, *where* $0 < \eta \equiv [1 + (1 - \varepsilon)\tau_M]/[(1 + t_C)(1 + \tau_M)] \leqslant 1$. *The dynamic system can be decomposed in two subsystems—one for investment and one for savings—with the following properties:*

[12] To check the validity of our log-linear approximation, we have also simulated the nonlinear version of the model by using the relaxation algorithm of Trimborn et al. (2008). The results obtained by using both methods are identical.

[13] Strictly speaking, the variable $\tilde{A}$ is not completely predetermined. The non-predetermined part of it, however, is already determined by the investment system.

Table 3.1: Summary of the Log-Linearized Model

(a) Dynamic Equations:

$$\dot{\tilde{K}} = \frac{r\omega_I}{\omega_K}\left(\tilde{I} - \tilde{K}\right) \quad \text{(T1.01)}$$

$$\dot{\tilde{q}} = r\left[\tilde{q} - \frac{\alpha_M}{1-\alpha_M}\frac{\omega_L^M}{\omega_K}\left(\tilde{Y}_M - \tilde{K} + \tilde{\tau}_M\right)\right] \quad \text{(T1.02)}$$

$$\dot{\tilde{X}} = (r-\rho)\left(\tilde{X} - \frac{\tilde{A}}{\omega_A}\right) \quad \text{(T1.03)}$$

$$\dot{\tilde{A}} = r\left[\tilde{A} + (\omega_L^E + \omega_L^M)(\tilde{L}_F + \tilde{w}) + \tilde{T} - \omega_X\tilde{X} + \omega_Y^S(\tilde{Y}_S + \tilde{t}_C)\right] \quad \text{(T1.04)}$$

$$\dot{\tilde{H}} = (r+\beta)\tilde{H} - r\left[(\omega_L^E + \omega_L^M)(\tilde{L}_F + \tilde{w}) + \tilde{T} + \omega_Y^S(\tilde{Y}_S + \tilde{t}_C)\right] \quad \text{(T1.05)}$$

$$\dot{\tilde{V}}_Z = r\left(\tilde{V}_Z - \omega_Z\tilde{r}_E\right) \quad \text{(T1.06)}$$

(b) Factor Markets and Production:

$$\tilde{w} = \tilde{\tau}_M + \alpha_M(\tilde{K} - \tilde{L}_M) = -\alpha_E\tilde{L}_E = \tilde{p}_A - \alpha_S\tilde{L}_S \quad \text{(T1.07)}$$

$$\tilde{r}_E = (1-\alpha_E)\tilde{L}_E \quad \text{(T1.08)}$$

$$\tilde{q} = \chi_K(\tilde{I} - \tilde{K}) \quad \text{(T1.09)}$$

$$\tilde{Y}_M = (1-\alpha_M)\tilde{L}_M + \alpha_M\tilde{K} \quad \text{(T1.10)}$$

$$\tilde{Y}_E = (1-\alpha_E)\tilde{L}_E \quad \text{(T1.11)}$$

$$\tilde{Y}_S = (1-\alpha_S)\tilde{L}_S \quad \text{(T1.12)}$$

$$0 = \omega_L^M\tilde{L}_M + \omega_L^E\tilde{L}_E + \omega_L^S\tilde{L}_S \quad \text{(T1.13)}$$

(c) Consumption, Goods Prices, and Revenue:

$$\tilde{C}_M = \tilde{C}_A - \tilde{\tau}_M, \quad \tilde{C}_A = \omega_C^E/(\omega_C^E + \omega_C^S)\tilde{C}_E + \omega_C^S/(\omega_C^E + \omega_C^S)\tilde{C}_S \quad \text{(T1.14)}$$

$$\tilde{X} = \tilde{p}_M + \tilde{C}_M = \tilde{p}_A + \tilde{C}_A \quad \text{(T1.15)}$$

$$\tilde{X} = \tilde{p}_C + \tilde{C}, \quad \tilde{p}_C = \varepsilon\tilde{p}_M + (1-\varepsilon)\tilde{p}_A \quad \text{(T1.16)}$$

$$\tilde{p}_M = \tilde{t}_C + \tilde{\tau}_M, \qquad \tilde{p}_A = \tilde{p}_E = \tilde{t}_C \quad \text{(T1.17)}$$

$$\tilde{T} = (\omega_C^E + \omega_C^M)\tilde{t}_C + \left(\omega_C^M - \frac{\omega_M^L}{1-\alpha_M}\right)\tilde{\tau}_M + \frac{t_C}{1+t_C}\omega_C^E\tilde{C}_E - \frac{\tau_M}{1+\tau_M}\frac{\omega_L^M}{1-\alpha_M}\tilde{Y}_M + \frac{t_C + \tau_M + t_C\tau_M}{(1+\tau_M)(1+t_C)}\omega_C^M\tilde{C}_M \quad \text{(T1.18)}$$

(d) Portfolio Equilibrium:

$$\tilde{A} = \omega_K(\tilde{q} + \tilde{K}) + \tilde{V}_Z + \tilde{F} \quad \text{(T1.19)}$$

Notes: The following definitions are used: $\omega_A \equiv rA/Y$, $\omega_I \equiv I/Y$, $\omega_K \equiv rqK/Y$, $\omega_L^i = wL_i/Y$ for $i = \{M, E, S\}$, $\omega_X \equiv X/Y$, $\omega_Y^S \equiv (1+t_C)Y_S/Y$, and $\chi_K \equiv -(I/K)\Psi''/\Psi' > 0$. A tilde ($\tilde{}$) denotes a relative change, for example, $\tilde{C}(z) \equiv dC(z)/C$. Time derivatives of variables are generally defined as $\dot{\tilde{X}}(z) \equiv d\dot{X}(z)/X$.

(i) *the investment system has two distinct real eigenvalues; that is,* $-h_1^* < 0$ *and* $r_1^* = h_1^* + r > 0$ *with* $\partial h_1^*/\partial \chi_K < 0$, $\lim_{\chi_K \to 0} h_1^* = \infty$, *and* $\lim_{\chi_K \to \infty} h_1^* = 0$; *and*

(ii) *the savings system has two distinct real eigenvalues; that is,* $-h_2^* < 0$ *and* $r_2^* = h_2^* + 2r - \rho > 0$ *with* $\partial h_2^*/\partial \beta > 0$ *and* $\lim_{\beta \to \infty} h_2^* = \infty$.

Proof. See Appendices 3.A.2 and 3.A.3. □

Deferring technical details to Appendix 3.A.2 and dropping time indices, the investment system can be written as:

$$\begin{bmatrix} \dot{\tilde{K}} \\ \dot{\tilde{q}} \end{bmatrix} = \begin{bmatrix} 0 & \delta_{12} \\ \delta_{21} & r \end{bmatrix} \begin{bmatrix} \tilde{K} \\ \tilde{q} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -\lambda_q & \gamma_q \end{bmatrix} \begin{bmatrix} \tilde{\tau}_M \\ \tilde{t}_C \end{bmatrix}, \tag{3.16}$$

where $\delta_{12} \equiv r\omega_I/(\chi_K \omega_K) > 0$, $\delta_{21} \equiv r(\omega_L^M)^2 \alpha_M \alpha_S \alpha_E/(|\Omega|\,\omega_K) > 0$, and $|\Omega| = \alpha_M \alpha_E \omega_L^S + \alpha_S \alpha_E \omega_L^M + \alpha_S \alpha_M \omega_L^E > 0$ is the determinant of the Jacobian matrix corresponding to the labor market equilibrium (Appendix 3.A.1). The GDP shares of the respective variables are defined as: $\omega_I \equiv I/Y$, $\omega_K \equiv rqK/Y$, and $\omega_L^i = wL_i/Y$ for $i = \{M, E, S\}$. The elements in the matrix of tax policy shocks are given by:

$$\lambda_q \equiv \frac{\alpha_M}{1-\alpha_M} \frac{r\omega_L^M}{\omega_K} \frac{\alpha_E \omega_L^S + \alpha_S \left(\omega_L^E + \alpha_E \omega_L^M\right)}{|\Omega|} > 0,$$
$$\gamma_q \equiv r \frac{\omega_L^M}{\omega_K} \frac{\alpha_M \alpha_E \omega_L^S}{|\Omega|} > 0,$$

and the shock terms are defined as $\tilde{\tau}_M \equiv d\tau_M/(1+\tau_M)$ and $\tilde{t}_C \equiv dt_C/(1+t_C)$. The investment system can be graphically summarized by the phase diagram in Panel (a) of Figure 3.1. The $\dot{\tilde{K}} = 0$ line represents combinations of $\tilde{q}$ and $\tilde{K}$ for which the capital stock is constant over time. The schedule is horizontal at $\tilde{q}^* = 0$, which corresponds to the steady-state value of Tobin's q for which $\Psi(.) = \delta$. If $\tilde{q}$ exceeds $\tilde{q}^*$, net investment will be positive. Conversely, $\tilde{q}$-values falling short of $\tilde{q}^*$ give rise to negative net investment, which is indicated by the horizontal arrows in the figure. The $\dot{\tilde{q}} = 0$ schedule shows combinations of $\tilde{q}$ and $\tilde{K}$ for which Tobin's q is constant over time. It is downward sloping, because a higher capital stock leads to a fall in the marginal product of capital and thus to a lower market value of capital in equilibrium. For points to the right of the $\dot{\tilde{q}} = 0$ schedule, the marginal product of capital is too low, so that part of the return to capital consists of capital gains. Conversely, for points to the left of $\dot{\tilde{q}} = 0$ schedule, the marginal product of capital is too high, giving rise to capital losses on investment. Hence, $\dot{\tilde{q}} > 0$ to the right of the line and $\dot{\tilde{q}} < 0$ to the left, as indicated by the vertical arrows in Figure 3.1. The arrow configuration confirms that the equilibrium at E_0 is saddle-point stable.

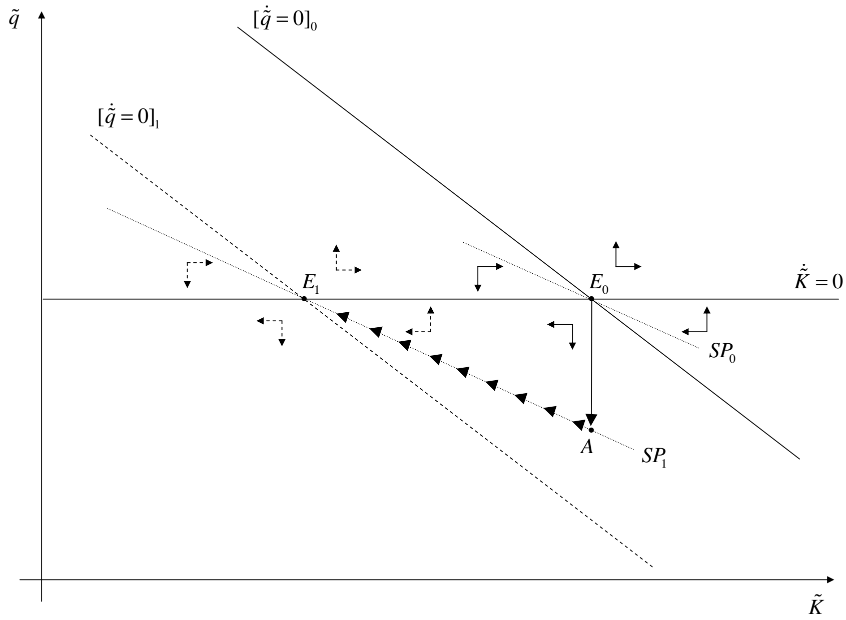
Again relegating the derivations to the appendix, the savings system can be written as:

$$\begin{bmatrix} \dot{\tilde{X}} \\ \dot{\tilde{A}} \end{bmatrix} = \begin{bmatrix} r-\rho & -\frac{r-\rho}{\omega_A} \\ -r\eta\omega_X & r \end{bmatrix} \begin{bmatrix} \tilde{X} \\ \tilde{A} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ \kappa_A & \lambda_A & \gamma_A \end{bmatrix} \begin{bmatrix} \tilde{K} \\ \tilde{\tau}_M \\ \tilde{t}_C \end{bmatrix}, \qquad (3.17)$$

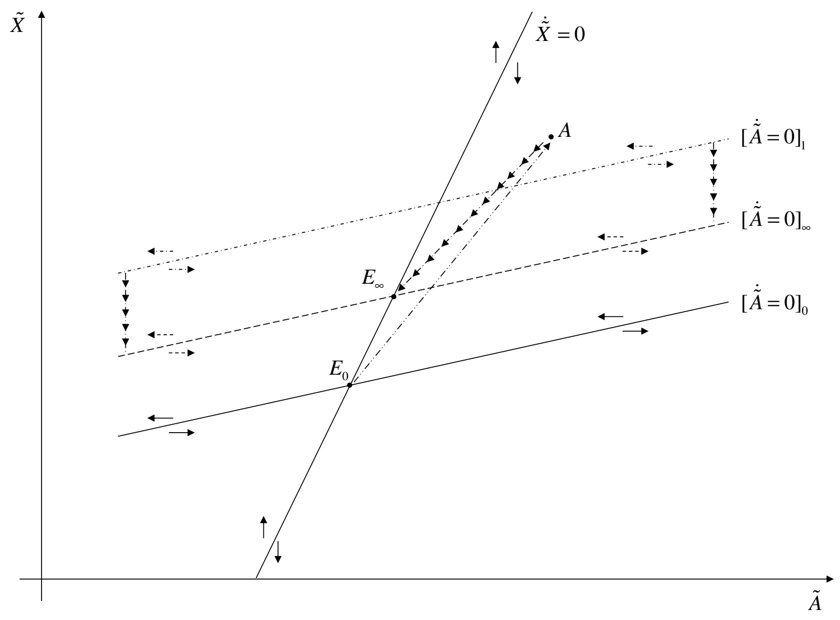
where $\omega_X \equiv X/Y$, $\omega_A \equiv rA/Y$, and the composite terms κ_A, λ_A, and γ_A are defined in Appendix 3.A.3. Pre-existing tax and tariff rates and the relative sector sizes determine the signs of these terms. Because the system features the capital stock in the second vector on the right-hand side of (3.17), the first shock term is time-varying and follows from the solution to the investment system (3.16). The savings system is graphically represented in Panel (b) of Figure 3.1. The $\dot{\tilde{X}} = 0$ line represents combinations of $\tilde{X}$ and $\tilde{A}$ for which aggregate full consumption is constant over time. The schedule is upward sloping, owing to the generational turnover effect; that is, larger financial wealth holdings by households increase the gap between consumption of newborn generations and aggregate full consumption so that aggregate full consumption must increase to keep the proportional gap constant. If financial wealth exceeds the equilibrium value, newborn generations are relatively poor so that aggregate full consumption declines over time. Conversely, if financial wealth falls short of the equilibrium value, aggregate full consumption increases. Hence, $\dot{\tilde{X}} < 0$ to the right of the line and $\dot{\tilde{X}} > 0$ to the left, as indicated by the vertical arrows in Figure 3.1. The $\dot{\tilde{A}} = 0$ locus depicts combinations of $\tilde{X}$ and $\tilde{A}$ for which financial wealth is constant. This schedule is also upward sloping, because an increase in financial wealth supports a higher level of full consumption. The slope of the $\dot{\tilde{X}} = 0$ line is steeper with respect to the $\tilde{A}$ axis than that of the $\dot{\tilde{A}} = 0$ schedule. For points above the $\dot{\tilde{A}} = 0$ schedule, full consumption is too high, leading to a decrease in financial wealth. Conversely, for points below the $\dot{\tilde{A}} = 0$ schedule, financial wealth rises. Hence, $\dot{\tilde{A}} < 0$ above the line and $\dot{\tilde{A}} > 0$ below the line, as indicated by the horizontal arrows in Figure 3.1. The arrow configuration again confirms that the equilibrium is saddle-point stable.

Figure 3.1: Phase Diagrams: The Investment and Savings System

(a) Investment System



(b) Savings System



Notes: Panel (b) describes a special case of the model, corresponding to the benchmark calibration. The financial wealth schedule shifts up at impact and remains above its initial position if and only if $\varepsilon\gamma_A - \lambda_A > 0$ and $\kappa_A(\varepsilon\gamma_q + \lambda_q) - \delta_{21}(\varepsilon\gamma_A - \lambda_A) < 0$, respectively. See also Appendix 3.A.3.2.

3.3.2 Calibration

To get insight into the quantitative allocation and welfare effects, we calibrate the model to match a typical low-income developing economy by using parameter values taken from the literature and derived from primary data. Table 3.2 provides an overview of the chosen parameter values. We set the world interest rate r to 4 percent (cf. Mendoza, 1991). We choose a value of $\beta = 0.033$ to match the average crude birth rate—which is assumed to equal the death rate—in low-income countries over the last decade (World Bank, 2010), implying an average expected working lifetime of 33.33 years. In order to get a reasonable imports-to-GDP share, the taste parameter ε is set to 0.55.

In line with Gollin (2002a), we set the output elasticity of labor in the import-substitution sector $1-\alpha_M$ to 0.67. Based on Valentinyi and Herrendorf (2008), who find that the labor income share in the agricultural sector is lower than that of the aggregate economy because of the large land income share, we use $1-\alpha_E = 0.5$ for the output elasticity of labor in the export sector. We assume that the production elasticity of labor in home production $1 - \alpha_S$ also takes on a value of 0.5. The productivity indexes of the formal sectors are chosen to get empirically plausible sectoral output levels as share of GDP. In keeping with the RBC literature (cf. Kydland and Prescott, 1982), the rate of depreciation δ is set to 0.10. We employ a logarithmic specification of the concave adjustment cost function:

$$\Psi\left(\frac{I}{K}\right) = \bar{z}\left[\ln\left(\frac{I}{K} + \bar{z}\right) - \ln\bar{z}\right],$$

where $\bar{z}$ is a parameter that regulates the concavity of the function and therefore the magnitude of the adjustment costs.[14] By choosing $\bar{z} = 1.25$, we obtain adjustment costs on the order of 0.4 percent of GDP, slightly above Mendoza (1991) and Heijdra and Ligthart (2010), who work with 0.1 and 0.2 percent of GDP, respectively.

The average collected import tariff rate in low-income countries is roughly 20 percent (cf. Ebrill et al., 1999).[15] Gordon and Li (2009) derive an average statutory VAT rate across 26 emerging market and developing countries of 14.7

[14] Using l'Hôpital's rule, it can be derived that $\lim_{\bar{z}\to\infty} \Psi(I/K) = I/K$, so that adjustment costs are zero for infinitely large values of $\bar{z}$.

[15] The collected import tariff rate is defined as tariff revenue divided by the import value (including cost, insurance, and freight) and is typically smaller than the statutory tariff rate, reflecting exemptions, evasion, and the like.

Table 3.2: The Parameter Values in the Benchmark Model

Description	Parameter	Value	Source
Preferences	ε	0.550	World Bank (2009), *World Development Indicators*
Demography	β	0.033	Average expected life span of 33.3 working years
World interest rate	r	0.040	Mendoza (1991)
Technology	α_E	0.500	Valentinyi and Herrendorf (2008)
	α_M	0.330	Gollin (2002)
	α_S	0.500	Valentinyi and Herrendorf (2008)
	Ω_E	1.000	World Bank (2009), *World Development Indicators*
	Ω_M	0.750	World Bank (2009), *World Development Indicators*
	Ω_S	0.850	Schneider and Enste (2002) and Parente et al. (2000)
Capital accumulation	δ	0.100	Mendoza (1991) and Mendoza and Tesar (2005)
	$\bar{z}$	1.250	Mendoza (1991)
Tax rates	t_C	0.125	Gordon and Li (2009)
	τ_M	0.200	Ebrill et al. (1999)

percent. Portes (2009) finds an *effective* consumption tax rate—defined as the ratio of consumption tax revenue to consumption—in Mexico of 8.4 percent. Therefore, we set the consumption tax rate to 12.5 percent, which lies in between the statutory value of Gordon and Li (2009) and the effective one reported by Portes (2009). These initial tax and tariff rates put the economy on the upward-sloping segment of the Laffer curve for total government revenue.

We normalize the stock of net foreign assets in the benchmark scenario to zero (i.e., $F(0) = 0$), which implies a pure rate of time preference of 2.9 percent. The two stable eigenvalues amount to $h_1^* = 0.204$ and $h_2^* = 0.018$. Hence, the convergence speed of the investment system is considerably higher than that of the savings system. A number of key steady-state macroeconomic shares derived in the calibration are reported in Table 3.3. Using data from the World Bank's (2009) *World Development Indicators*, we find that the employment share of the agricultural sector has been around 53 percent over the last decade in lower middle income countries. Our implied employment share of 50 percent comes close to this number. Over the last decade, imports of goods and services as a share of GDP averaged around 41 percent in low-income countries (cf. World Bank, 2010). This number is roughly in line with the implied share of 0.43.

The implied investment-to-GDP share of 9 percent falls short of the average GDP share of gross capital formation in low-income countries, which amounted to 19 percent during the last decade (cf. World Bank, 2010). For our setup, without government investment and where private investment is only possible in the import-substitution sector, a figure of 9 percent does not seem unreasonable. The implied public revenue-to-GDP share amounts to 16 percent, which is within the range of 14.1 to 16.7 percent that Gordon and Li (2009) find for low-income countries. Schneider and Enste (2002, p. 31) report informal sector GDP-shares in African countries varying from 20 to 76 percent. By picking an appropriate value of the productivity index of the informal sector, we obtain an implied home production share of 47 percent which is in the middle of this range.

3.4 Dynamic Allocation Effects

This section considers the dynamic allocation effects of a simple strategy of offsetting a tariff rate cut (i.e., $\tilde{\tau}_M < 0$) by an increase in the destination-based consumption tax (i.e., $\tilde{t}_C = -\varepsilon\tilde{\tau}_M > 0$) so as to leave the consumer price index

Table 3.3: Macroeconomic Shares

Share	Definition	Value
ω_A	rA/Y	0.293
ω_C^M	$(1+t_C)(1+\tau_M)C_M/Y$	0.787
ω_C^E	$(1+t_C)C_E/Y$	0.175
ω_C^S	$(1+t_C)C_S/Y$	0.468
ω_H	rH/Y	0.623
ω_I	I/Y	0.088
ω_K	rqK/Y	0.037
ω_L^E	wL_E/Y	0.256
ω_L^M	wL_M/Y	0.252
ω_L^S	wL_S/Y	0.234
ω_T	T/Y	0.161
ω_Y^E	$(1+t_C)Y_E/Y$	0.576
ω_Y^M	$(1+t_C)(1+\tau_M)Y_M/Y$	0.424
ω_Y^S	$(1+t_C)Y_S/Y$	0.468
ω_X	X/Y	1.430
ω_{XE}	X_E/Y	0.432
ω_{XM}	X_M/Y	0.432
ω_Z	$r_Z Z_E/Y$	0.256

Notes: The shares are based on the parameters of the benchmark simulation. Note that $\omega_F \equiv rF/Y = 0$.

unchanged; that is, $\tilde{p}_C = 0$. We assume an exogenously given initial tax and tariff system. The policy change is permanent and unanticipated in the sense that it is simultaneously announced and implemented on a permanent basis. We first discuss analytical allocation results for the investment system, the labor market, and the savings system before we turn to a quantitative analysis.

3.4.1 Analytical and Graphical Analysis

3.4.1.1 Investment System

The time paths of the capital stock and Tobin's q induced by the tax-tariff reform are given by (Appendix 3.A.2.2):

$$\tilde{q}(t) = \frac{\lambda_q + \varepsilon\gamma_q}{r_1^*} e^{-h_1^* t}\tilde{\tau}_M, \tag{3.18}$$

$$\tilde{K}(t) = \frac{\delta_{12}}{h_1^*}\frac{\lambda_q + \varepsilon\gamma_q}{r_1^*}\left(1 - e^{-h_1^* t}\right)\tilde{\tau}_M, \tag{3.19}$$

where h_1^* measures the convergence speed of the investment system. The impact (or short-run) effect of the reform corresponds to $t = 0$ and the long-run effect takes $t \to \infty$. From (3.18)–(3.19), it can easily be seen that $\tilde{q}(0)/\tilde{\tau}_M > 0$, $\tilde{q}(\infty)/\tilde{\tau}_M = 0$, and $\tilde{K}(\infty)/\tilde{\tau}_M > 0$ (recall $\tilde{\tau}_M < 0$).

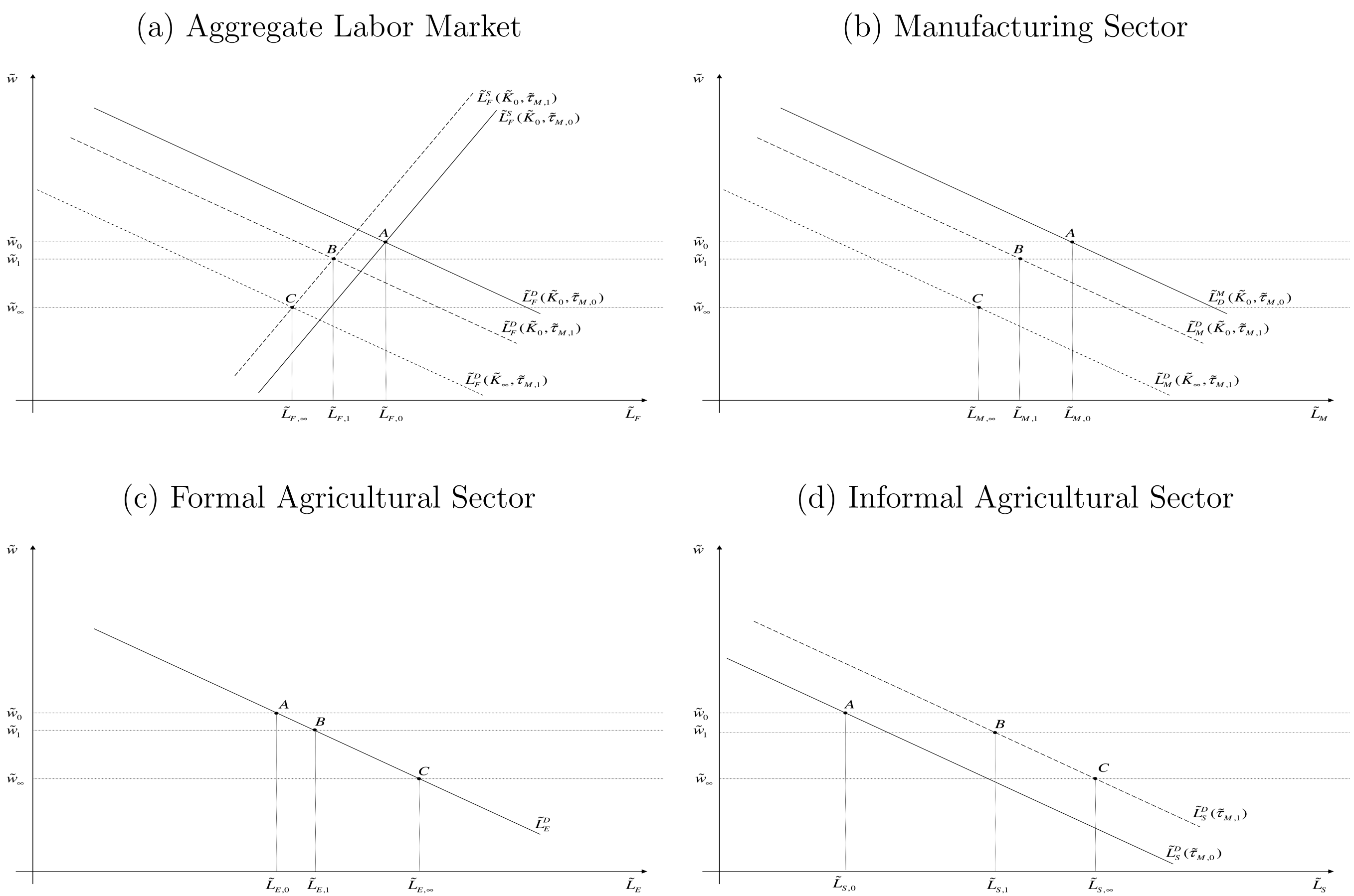
Panel (a) of Figure 3.1 shows that the reform shifts down the $\dot{\tilde{q}}(t) = 0$ locus from $[\dot{\tilde{q}}(t) = 0]_0$ to $[\dot{\tilde{q}}(t) = 0]_1$, whereas the $\dot{\tilde{K}}(t) = 0$ locus remains unaffected. On impact, Tobin's q jumps down, because the drop in the import tariff directly decreases the marginal product of capital in the import-substitution sector. The accompanying increase in the consumption tax rate amplifies the fall in Tobin's q through a reallocation of workers from the formal to the informal sector, which further decreases the marginal product of capital in the import-substitution sector. In the figure, the jump in Tobin's q is represented by the movement from the initial equilibrium E_0 to point A on the saddle path SP_1. The drop in the firm's discounted cash flows depresses gross investment, causing the capital stock in the manufacturing sector to fall over time. During transition, the marginal product of capital increases, so that Tobin's q slowly recovers until it equals its pre-shock level again. The economy moves from point A along the saddle path to the new steady state E_1, which lies to the left of the old equilibrium E_0.

3.4.1.2 Aggregate and Sectoral Labor Markets

Panel (a) of Figure 3.2 shows the effect of the reform on the aggregate formal labor market and Panels (b)–(d) depict the sectoral labor markets.[16] The initial equilibrium is located at the points labeled A on the solid lines in the four panels. On impact, the tariff cut shifts the labor demand curve in the import-substitution sector to the left [Panel (b), dashed line], reflecting a lower domestic price of import substitutes. Because the labor demand curve in the export sector is not affected [Panel (c), solid line], the aggregate formal labor demand curve also shifts leftward [Panel (a), negatively sloped dashed line]. Moreover, the accompanying increase in the consumption tax rate shifts the labor supply curve in the informal sector to the right [Panel (d), dashed line], and hence the aggregate formal labor supply curve moves to the left [Panel (a), positively sloped dashed line]. As a result, informal employment expands on impact at the expense of employment in the aggregate market sector. Note that in Panel (a) the shift of the aggregate formal

[16] The corresponding expressions for the labor supply and demand curves are given in (T1.07), (T1.13), (A.3.7), and (A.3.8). The solution to the labor market system is given by (A.3.3)-(A.3.6).

Figure 3.2: Aggregate and Sectoral Labor Market Equilibrium



Notes: Panel (b) is based on equation (3.14a), Panel (c) on (3.11), and Panel (d) on (3.4c). Panel (a) follows from $L_F = L_M + L_E$ and $L_S = 1 - L_F$. The dashed and dotted lines represent short-run and transitional responses, respectively.

labor demand curve dominates the shift in the aggregate formal labor supply curve, implying a lower wage rate on impact; that is, $\tilde{w}_1 < \tilde{w}_0$.[17] As a result, employment in the formal agricultural sector goes up immediately. The short run changes in employment and the wage rate are represented by the move from points A to points B in the four panels.

Panel (b) of Figure 3.2 shows that the transitional decrease in the capital stock shifts the labor demand curve of the import-substitution sector further to the left (see the dotted line). Because the labor demand curve in the export sector is not affected [Panel (c), solid line], the aggregate formal labor demand curve shifts leftward too [Panel (a), dotted line]. The labor supply curve of the informal sector does not depend on the physical capital stock, implying that the formal labor supply curve remains unchanged [Panel (a), positively sloped dashed line]. Consequently, the market wage rate decreases from $\tilde{w}_1$ to the new steady-state level $\tilde{w}_\infty = \tilde{\tau}_M/(1-\alpha_M) < 0$ and equilibrium employment in the formal sector falls from $\tilde{L}_{F,1}$ to $\tilde{L}_{F,\infty}$ [Panel (a) of Figure 3.2]. The effect of the transitional decrease in the capital stock on the wage rate and on employment in the different sectors is represented by the move from points B to points C in the four panels.

3.4.1.3 Savings System

This section focuses on the short-run and long-run effects of the tax-tariff reform on full consumption and financial assets. To keep the discussion simple, we defer the analytical solutions for the time paths of full consumption and financial wealth to Appendix 3.A.3. The jump in aggregate financial wealth is determined by the investment system and is composed of changes in the value of the firm in the import-competing sector and in the value of land:

$$\tilde{A}(0) = \omega_K \tilde{q}(0) + \tilde{V}_Z(0) = \omega_K \frac{\lambda_q + \varepsilon\gamma_q}{h_1^* + r}\left[1 - \frac{\omega_L^E}{\omega_L^M}\frac{1}{1+t_C}\frac{(1-\alpha_E)}{\alpha_E}\frac{h_1^*}{r}\right]\tilde{\tau}_M \\ - \omega_Z(1-\alpha_E)\frac{\alpha_S\omega_L^M - \varepsilon\alpha_M\omega_L^S}{|\Omega|}\tilde{\tau}_M, \qquad (3.20)$$

where $\omega_Z \equiv r_Z/Y$ and the terms on the right-hand side of the equality sign are obtained by substituting (3.18) at $t = 0$ and $\tilde{V}_Z(0)$ (Appendix 3.A.3.4). The first term between brackets captures the direct negative effect of a fall in Tobin's q on financial wealth. The second term represents the increase in the value of

[17] The sign of the short-run wage change is equal to the sign of the term $\varepsilon\alpha_M\omega_L^S - \alpha_S\omega_L^M$ [see (A.3.6)].

land induced by the future increase in agricultural employment. Intuitively, as the capital stock diminishes, part of the workers in the import-substitution sector move to the export sector, thereby increasing the marginal product of land. Note that this effect is absent when capital mobility is zero (i.e., $\chi_K \to \infty$ and thus $h_1^* = 0$). The last term of (3.20) captures the static labor reallocation effect. In economic terms, the cut in the import tariff rate decreases employment in the manufacturing sector, thereby increasing the number of workers and the marginal product of land in the export sector (first term in the numerator). In contrast, the accompanying increase in the consumption tax induces workers to move to the informal sector, which decreases employment and the marginal product of land in the export sector (second term in the numerator).

The net impact effect on financial wealth depends strongly on the relative employment shares ω_L^E/ω_L^M, the adjustment speed of the investment system h_1^*, and the size of the informal sector ω_L^S. As long as the export sector is large compared to the import-substitution sector and the adjustment speed is not too small, the term between brackets is negative, thereby raising financial wealth (because $\tilde{\tau}_M < 0$). Intuitively, a large relative size of the export sector implies a large share of land in households' wealth portfolios; in that case, the effect of the change in the value of land dominates that of the change in the value of physical capital. Moreover, the jump in the value of land is positively affected by the adjustment speed h_1^* via a more rapid increase in the marginal product of land and a smaller decline in Tobin's q. The term on the second line of (3.20) is negative as long as the informal sector size is not too large and thus immediately boosts financial wealth in that case. The reason is that the direct labor reallocation effect of the tariff cut then dominates that of the consumption tax rate increase, so that the marginal product of land in the export sector rises.

According to (3.6), full consumption depends on the change in financial wealth and human capital. The jump in full consumption is given by:

$$\tilde{X}(0) = \frac{h_2^* + \rho}{r\eta\omega_X}\tilde{A}(0) + \frac{1}{r\eta\omega_X}\frac{h_2^* + \rho}{h_2^* + r}\left[h_1^*\frac{\kappa_A(\lambda_q + \varepsilon\gamma_q)}{\delta_{21}(h_1^* + h_2^* + r)} - (\varepsilon\gamma_A - \lambda_A)\right]\tilde{\tau}_M. \tag{3.21}$$

The first term represents the effect of the short-run change in financial wealth, whereas the second term accounts for the effect of human capital on full consumption. Human capital is negatively affected by the future decrease in the capital stock, which depresses the wage rate (first term between brackets).[18] Note that this intertemporal effect disappears when capital mobility is zero (i.e., $h_1^* = 0$). The second term between brackets captures the (static) effect on the return to human capital for a given level of the physical capital stock, which is positive as long as the employment share of the informal sector is not too large.[19]

In the long run, full consumption and financial wealth change according to:

$$\tilde{X}(\infty) = \frac{1}{\omega_A}\tilde{A}(\infty) = \frac{(r-\rho)\left[\delta_{21}(\varepsilon\gamma_A - \lambda_A) - \kappa_A(\varepsilon\gamma_q + \lambda_q)\right]}{\delta_{21}\omega_A \left|\Delta^I\right| \left|\Delta^S\right|}\tilde{\tau}_M, \tag{3.22}$$

where $\left|\Delta^I\right| < 0$ and $\left|\Delta^S\right| < 0$ (if $r < \rho + \eta\beta$, which is required for saddle-path stability of the equilibrium, see Proposition 3.1) are the determinants of the investment system and savings system, respectively (see Appendices 3.A.2 and 3.A.3). The first term between brackets in the numerator on the right-hand side represents the static effect on the return to human capital for a given physical capital stock, which is positive as long as the employment share of the informal sector is not too high (see footnote 19). The second term captures the intertemporal effect of the decrease in the capital stock. Section 3.4.2 demonstrates that the size of the informal sector has an important bearing on the signs of the long-run net effect on full consumption and financial wealth.

Panel (b) of Figure 3.1 illustrates the dynamic effects of the reform on the savings system. The phase diagram is drawn for the case in which the long-run effects on full consumption and financial wealth are positive, which corresponds to the benchmark scenario in Section 3.4.2. Moreover, it is assumed that the employment share of the informal sector is not too big and that the employment share of the export sector is not too small (see Appendix 3.A.3.2). The reform shifts up the $\dot{\tilde{A}} = 0$ schedule to $[\dot{\tilde{A}} = 0]_1$, whereas $\dot{\tilde{X}} = 0$ remains unaffected. Initially, the economy jumps from the old equilibrium E_0 to point A. Subsequently, as the capital stock starts decumulating, the $\dot{\tilde{A}} = 0$ locus gradually shifts down so that the economy moves from point A to the new long-run equilibrium E_∞.

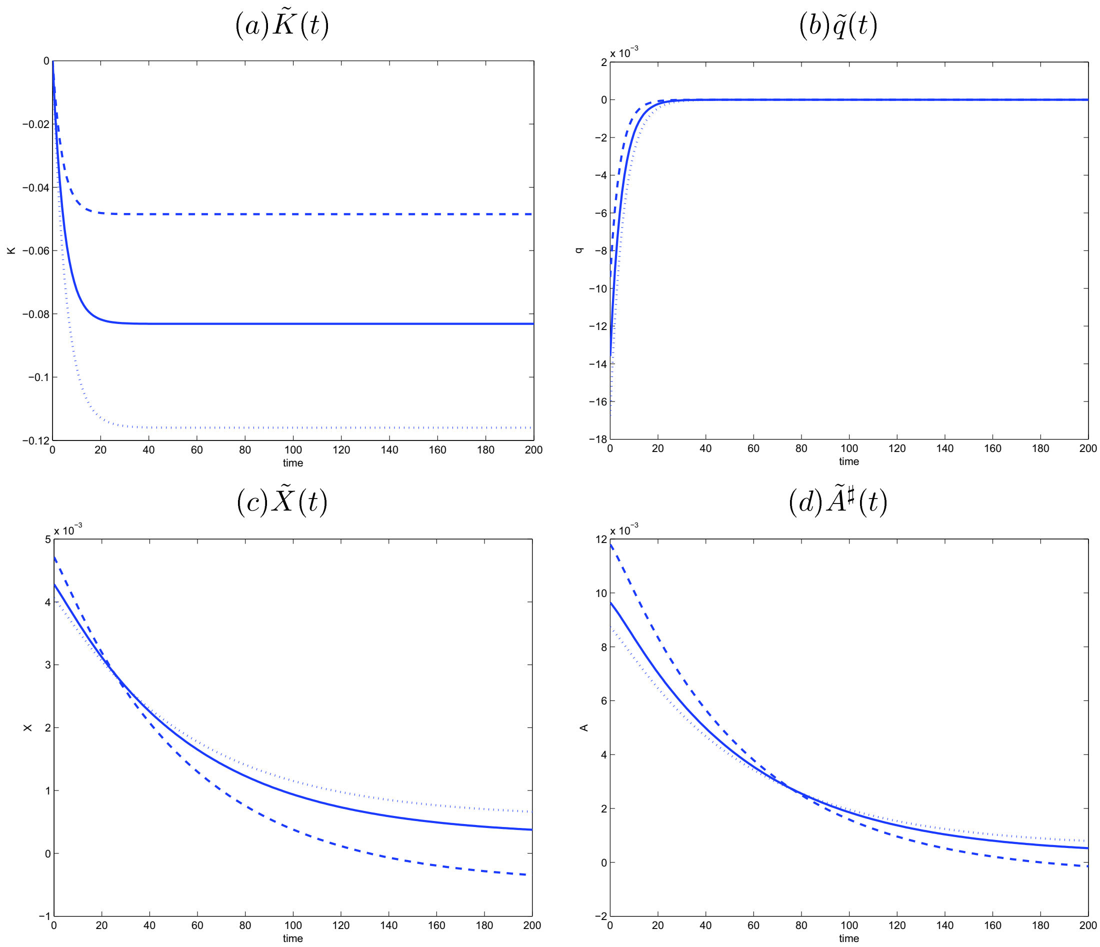
3.4.2 Quantitative Transitional Dynamics

To get insight into the transitional dynamic effects of the coordinated tax-tariff reform, we simulate the calibrated model. In the simulations, we use the analytical

[18]We assume $\kappa_A > 0$, implying that the effect of the capital stock on financial wealth and human capital is not dominated by the indirect effect that operates through lump-sum transfers.

[19]In Appendix 3.A.3.2, we derive sufficient conditions for $\varepsilon\gamma_A - \lambda_A > 0$, which are easily satisfied for plausible parameter values.

Figure 3.3: Transitional Dynamics



Notes: The dashed line denotes the scenario of $\omega_Y^S = 0.20$, the solid line represents $\omega_Y^S = 0.47$, and the dotted line depicts $\omega_Y^S = 0.63$. The other parameters are set at their benchmark values. The policy shock consists of $\tilde{\tau}_M = -0.01$ and $\tilde{t}_C = -\varepsilon\tilde{\tau}_M$. Variables with $\sharp$ in the superscript are scaled by their relative steady-state values instead of by Y.

impulse response functions derived in Appendices 3.A.2.2–3.A.3.3. The size of the tariff rate cut is set to $\tilde{\tau}_M = -0.01$. This corresponds with a reduction of 6 percent, which is equal to the average reduction of applied tariffs on industrial goods under the Uruguay Round Agreement (cf. Finger et al., 1996). To examine the importance of the informal sector, we distinguish three scenarios with a different output share of the informal sector $\omega_Y^S \equiv (1+t_C)Y_S/Y$ by varying the productivity parameter Ω_S; the latter takes on the values 0.60, 0.85 (benchmark), and 0.95 to arrive at values for ω_Y^S of 0.20, 0.47 (benchmark), and 0.63, respectively. Figure 3.3 shows the time profiles of the four state variables of the dynamic system (K,

q, X, and A). The number of periods that we show differs between the investment system and the savings system, because of differing adjustment speeds between the systems. We use time horizons of 40 and 200 periods for the investment and savings system, respectively, where each period corresponds to a year. Table 3.4 reports both the short-run and long-run effects on all macroeconomic variables of interest. The solid lines in Figure 3.3 and the middle column of Table 3.4 correspond to the benchmark scenario. We keep the pure rate of time preference fixed across scenarios and use the initial stock of net foreign assets as a calibration parameter. In the remainder of this section, we will first describe Figure 3.3 and then turn to the results in Table 3.4.

3.4.2.1 State Variables

Three observations stand out from the time paths shown in Figure 3.3. First, the transitional decrease in the capital stock and the downward jump in Tobin's q are more pronounced if the informal sector size is large (see the dotted lines in the figure). The reason is that, after the reform, more labor will we reallocated to the informal sector if this sector was already relatively large. As a result, the marginal product of capital, Tobin's q, and investment are affected negatively. Second, Figure 3.3 reveals that the net impact effect on financial wealth is positive in all scenarios. Accordingly, the positive jump in the value of land dominates the fall in Tobin's q, because the employment share of the export sector compared to that of the import-substitution sector and the adjustment speed of the investment system are large enough. Full consumption also jumps up, implying that the negative effect of the lower future physical capital stock is not strong enough to outweigh the immediate increase in financial wealth and the positive static effect on the return to human capital. The time profiles of financial wealth and full consumption are downward sloping, owing to a rising population share of new generations, who did not benefit from the increase in financial wealth at the time of the policy reform. The jumps in financial wealth and full consumption are decreasing in the informal sector size, because a larger informal sector amplifies the fall in Tobin's q and dampens the initial increase in the value of land. In the long run, however, the increase in both financial wealth and full consumption rises with the size of the informal sector. Intuitively, a larger informal sector increases the importance of income from home production for human capital, which positively affects the long-run change in human capital. Finally, Figure 3.3 shows that the long-run

Table 3.4: Short-Run and Long-Run Allocation Effects (in Percent)

	$\omega_Y^S = 0.47$		$\omega_Y^S = 0.20$		$\omega_Y^S = 0.63$	
	0	∞	0	∞	0	∞
State Variables						
$\tilde{K}$	0.000	-8.316	0.000	-4.849	0.000	-11.599
$\tilde{q}$	-1.359	0.000	-0.940	0.000	-1.674	0.000
$\tilde{A}^\sharp$	0.964	0.027	1.180	-0.049	0.873	0.057
$\tilde{X}$	0.428	0.027	0.471	-0.049	0.406	0.057
Labor Market						
$\tilde{L}_M$	-2.150	-6.824	-1.419	-3.357	-2.552	-10.106
$\tilde{L}_E$	0.581	2.985	1.063	2.985	0.315	2.985
$\tilde{L}_F$	-0.774	-1.882	-0.403	-0.762	-0.920	-2.656
$\tilde{L}_S$	1.681	4.085	2.163	4.085	1.415	4.085
$\tilde{w}$	-0.290	-1.493	-0.532	-1.493	-0.158	-1.493
Production						
$\tilde{Y}_M$	-1.441	-7.316	-0.951	-3.849	-1.710	-10.599
$\tilde{Y}_E$	0.290	1.493	0.532	1.493	0.158	1.493
$\tilde{Y}_F$	-0.367	-1.853	-0.180	-1.100	-0.424	-2.290
$\tilde{Y}_S$	0.840	2.043	1.082	2.043	0.708	2.043
Consumption						
$\tilde{C}_M$	0.878	0.477	0.921	0.401	0.856	0.507
$\tilde{C}_E$	-2.696	-7.387	-0.925	-2.525	-4.976	-14.880
Government Revenue						
$\tilde{T}^\sharp$	2.091	3.309	5.377	6.373	0.992	2.310
$\tilde{T}$	0.336	0.532	0.534	0.633	0.199	0.464
Current Account						
$\tilde{X}_E$	1.594	5.369	2.351	6.511	1.277	5.061
$\tilde{X}_M$	-1.648	5.170	-3.969	7.939	-1.162	4.650
$\tilde{F}$	0.000	-0.071	0.000	-0.113	0.000	-0.043

Notes: The parameters are set at their benchmark values in the first column. In the second and third column, Ω_S is changed to 0.60 and 0.95, implying $\omega_Y^S = 0.20$ and $\omega_Y^S = 0.63$, respectively. The policy shock consists of $\tilde{\tau}_M = -0.01$ and $\tilde{t}_C = -\varepsilon\tilde{\tau}_M$. To facilitate a sound comparison between the scenarios, variables with a dagger $\sharp$ in the superscript are scaled by their relative steady-state values instead of by Y.

effects on full consumption and financial wealth become negative if the informal sector is relatively small. In terms of Panel (b) of Figure 3.1, the $\dot{\tilde{A}} = 0$ locus shifts down beyond its initial steady-state position.

3.4.2.2 Employment and Output

The results in Table 3.4 show that the qualitative labor market and output effects are robust to changes in ω_Y^S. A larger informal sector (see the last two columns on the right) leads to a permanently larger fall in output and employment in both the manufacturing and aggregate market sector. The decline in the wage rate is less pronounced in the short run if the informal sector is large, because formal labor supply then decreases by more. Accordingly, a larger informal sector temporarily dampens the increase in formal agricultural employment and output, and vice versa. The effect on long-run wages, however, is independent of the size of the informal sector. Since the rental rate of capital is fixed, the change in the long-run capital-labor ratio in the import-competing sector—and associated with it the change in the steady-state wage rate—is fully determined by the change in the import tariff rate. Accordingly, the increases in both formal and informal agricultural employment and output in the long run are not affected by the size of the informal sector.

3.4.2.3 Consumption

The import tariff cut lowers the relative price of the imported consumption good, so that consumption of the manufactured good increases both in the short and long run (Table 3.4). Informal goods consumption also goes up, because the higher consumption tax rate induces households to substitute informal goods for formal agricultural goods. Because the time profile of full consumption is negatively sloped (Figure 3.3), consumption of both formal goods decreases over time. However, consumption of the informal good increases during the transition, owing to expanding home production as workers are leaving the import-substitution sector. A larger informal sector amplifies the decrease in the consumption of formal agricultural goods, as more labor is relocated to production of informal agricultural goods.

3.4.2.4 Government Revenue

As shown in Table 3.4, the tax-tariff reform leads to an increase in government revenue, in the short run as well as the long run. Although tariff revenue goes down on impact, this is more than offset by an increase in consumption tax revenue, owing to a larger consumption tax base (which includes both domestic and imported goods). In the long run, both the consumption tax and the import tariff generate more revenue than before the reform. Import tariff revenue increases, reflecting a positive tariff base effect that dominates the negative tariff rate effect in the long run. The base of the import tariff expands as the country imports more consumption goods. Intuitively, manufacturing output falls, whereas consumption of manufactured goods expands. The increase in public revenue depends negatively on the informal sector size, through its effect on the consumption tax base.

3.4.2.5 Current Account

The bottom rows of Table 3.4 show that the current account of the balance of payments turns into surplus in the short run—reflecting an immediate fall in investment—so that net foreign assets start to accumulate. At the same time, however, imports of manufactured goods rise by more than exports of formal agricultural goods. In the medium run, when the level of investment has settled down at its new equilibrium value, a deficit on the trade account materializes, so that net foreign assets go down and even become negative. A larger informal sector magnifies the decrease in investment by boosting the fall in Tobin's q, implying that the decline in steady-state net foreign assets becomes smaller.

3.5 Welfare Effects

This section investigates the welfare effects of a consumer price-neutral tax-tariff reform starting from the calibrated equilibrium. We first discuss the special case of infinite planning horizons of households, so that only the pure efficiency effect of the reform is present. Subsequently, we analyze the effects on the intergenerational welfare distribution using the finite-horizon model.

3.5.1 Efficiency Effects

3.5.1.1 Command Outcome versus Decentralized Market Outcome

We first look at the infinite-horizon model (i.e., $\beta = 0$) as a special case. In this case, the model only features a steady state if the 'knife-edge' condition $r = \rho$ holds. The first-best outcome follows from a command economy in which a social planner can allocate resources directly. The social planner's optimization problem yields the following optimality conditions:

$$\frac{\varepsilon}{1-\varepsilon}\frac{C_A(t)}{C_M(t)} = 1, \tag{3.23a}$$

$$(1-\alpha_S)\Omega_S L_S(t)^{-\alpha_S} = (1-\alpha_M)\Omega_M \left(\frac{K(t)}{L_M(t)}\right)^{\alpha_M} = (1-\alpha_E)\Omega_E \left(\frac{Z_E}{L_E(t)}\right)^{\alpha_E}, \tag{3.23b}$$

$$\frac{\dot{q}(t) + \alpha_M \frac{Y_M(t)}{K(t)}}{q(t)} = r + \delta - \left[\Psi\left(\frac{I(t)}{K(t)}\right) - \frac{1}{q(t)}\frac{I(t)}{K(t)}\right]. \tag{3.23c}$$

Let us first analyze the case without an informal sector (i.e., $\Omega_S = 0$), so that the first equality of (3.23b) drops out. Comparing (3.23a)–(3.23c) with (3.4a), (3.4b), (3.11), and (3.14a)–(3.14c) reveals that the decentralized market equilibrium only coincides with the social planner's solution if $\tau_M = 0$. Intuitively, there are no externalities in the model so that the tariff rate is the only variable distorting agents' decisions on consumption, production, and investment. Because of the tariff distortion, too much capital and labor is allocated to the manufacturing sector and too little of the manufactured good is consumed domestically. The consumption tax is allowed to take on any value, because it does not distort the allocation of consumption across agricultural goods and manufactured goods. Therefore, starting from a positive pre-existing import tariff rate, the consumer price-neutral tax-tariff reform always improves welfare.

If an informal sector is present (i.e., $\Omega_S > 0$), then the first equality on the left-hand side of (3.23b) must hold. Consequently, the consumption tax is no longer irrelevant for welfare purposes, because it then distorts the allocation of labor between the formal and informal sector, as shown in (3.4b). The decentralized market economy now only coincides with the planner's solution if $t_C = \tau_M = 0$. Starting from positive pre-existing consumption tax and tariff rates, the consumer price-neutral tax-tariff reform alleviates the tariff distortion at the cost of exacerbating the consumption tax distortion. Hence, the sign of the welfare change depends on the relative magnitudes of these two effects.

3.5.1.2 Welfare Results

By log-linearizing (3.1), while using (3.4a) and (3.5), we obtain the change in lifetime indirect utility:[20]

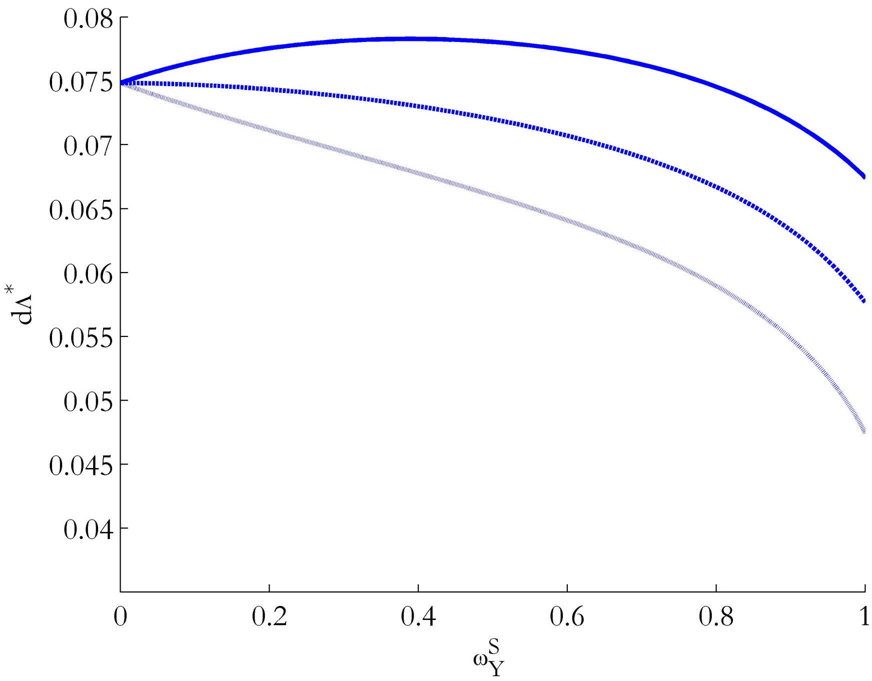
$$d\Lambda_{RA}^{*}(t) = \frac{\tilde{X}_{RA}(t)}{\rho} - \int_{t}^{\infty} \tilde{p}_C(z)e^{-\rho(z-t)}dz = \frac{\tilde{X}_{RA}(t)}{\rho},$$

where we use the subscript RA to distinguish variables in the infinite planning horizon case from their counterparts in the overlapping generations formulation. The size of the informal sector has two opposing effects on the welfare change induced by the tax reform: a larger informal sector (i) amplifies the increase in the consumption tax distortion yielding a negative effect on the welfare change); and (ii) amplifies the decrease in the tariff distortion (yielding a positive effect on the welfare change). If the pre-existing consumption tax distortion is large compared to the pre-existing import tariff distortion, the negative effect dominates the positive effect so that a larger informal sector negatively influences the change in welfare. Conversely, if the pre-existing import tariff distortion is large compared to the pre-existing consumption tax distortion, the positive effect on the welfare change exceeds the negative effect for a specific range of informal sector sizes.

Figure 3.4 studies the effect of the informal sector size on the welfare change by varying the initial consumption tax rate. The welfare change is a monotonically negative function of the informal sector size if the initial consumption tax rate is high, whereas the relationship is non-monotonous if the initial consumption tax is low. On the upward-sloping part of the schedule, the fall in the tariff rate distortion dominates the rise in the consumption tax distortion, whereas on the downward-sloping part the rise in the consumption tax distortion is dominant. Although the pure efficiency effect may thus be decreasing in the size of the informal sector, it remains positive for all empirically plausible pre-existing tax and tariff rates. Figure 3.5 depicts two unrealistic parameter settings, in which case the welfare effect does become negative. In Panel (a), we choose a rather high consumption

[20] The term capturing the price effect on lifetime welfare drops out, reflecting the price-neutrality of the tax-tariff reform.

Figure 3.4: Welfare Effects under Infinite Horizons: Plausible Cases



Notes: The pre-existing tax and tariff rates are: $\tau_M = 0.20$, $t_C = 0.125$ (solid line), $t_C = 0.175$ (dotted line), and $t_C = 0.225$ (gray line). The policy shock consists of $\tilde{\tau}_M = -0.01$ and $\tilde{t}_C = -\varepsilon\tilde{\tau}_M$.

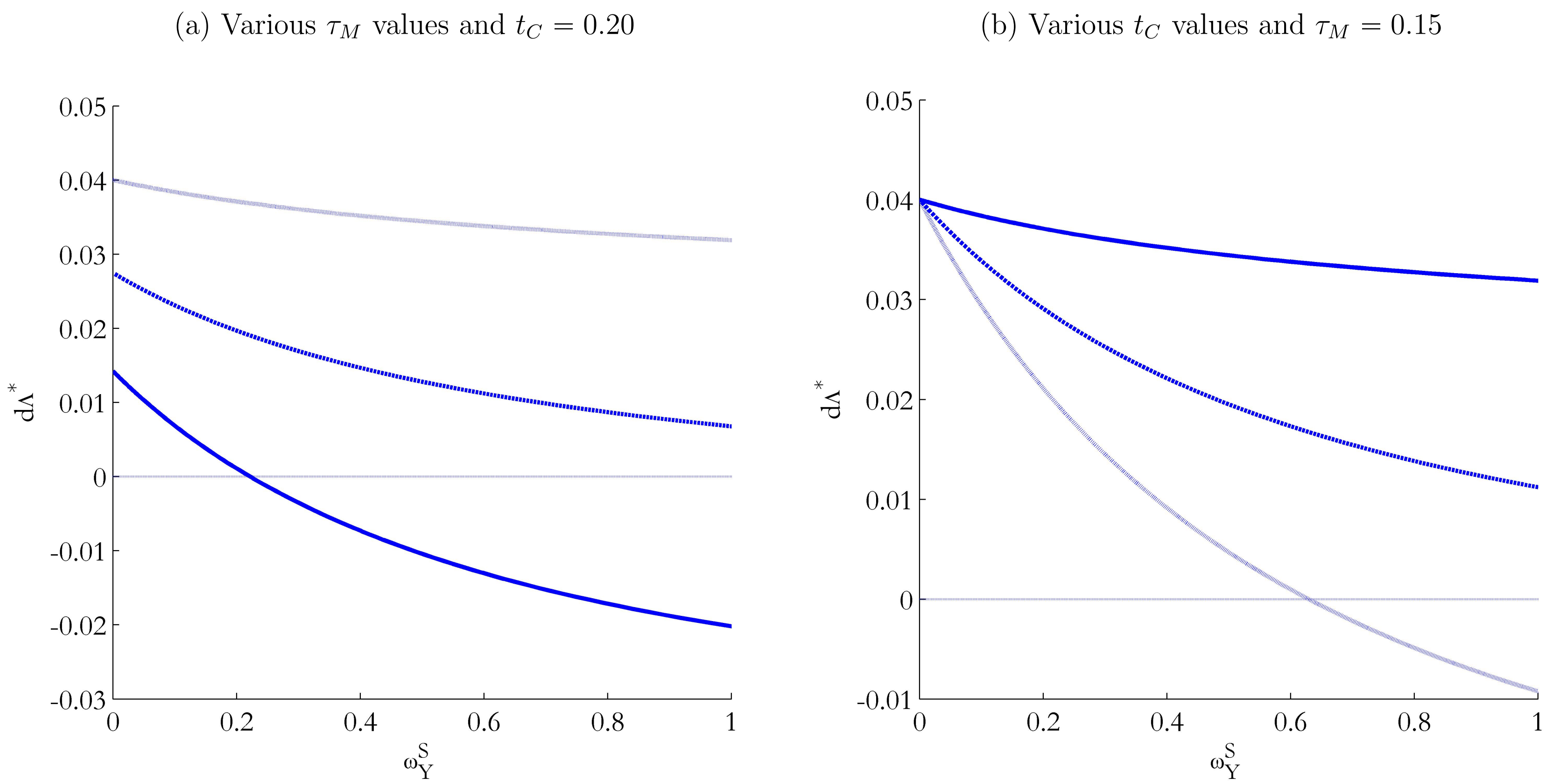
tax rate (i.e., $t_C = 0.20$) and vary the import tariff rate between 0.05 and 0.15. In Panel (b), we set an unrealistically low import tariff rate (i.e., $\tau_M = 0.05$) and pick values of the consumption tax rate in the range 0.10 and 0.30. Hence, only the combination of an unrealistically low import tariff rate and a rather high consumption tax rate renders the welfare effect negative.

Our welfare findings for plausible conditions differ qualitatively from the results derived in a static model with an informal sector (cf. Emran and Stiglitz, 2005), because we take into account the distortionary effect of import tariffs on the investment decision of firms. As a result, a reduction in the import tariff rate is more beneficial in a dynamic model than in a static constellation.

3.5.2 Intergenerational Distribution Effects

We now turn to the model with a positive birth rate (i.e., $\beta > 0$), where we have to take into account that generations differ in the amount of wealth they have accumulated and therefore are affected differently by the reform. We distinguish

Figure 3.5: Welfare Effects under Infinite Horizons: Extreme Cases



Notes: In Panel (a), the pre-existing tax and tariff rates are: $t_C = 0.20$, $\tau_M = 0.05$ (solid line), $\tau_M = 0.10$ (dotted line), $\tau_M = 0.15$ (gray line). In Panel (b), the pre-existing tax and tariff rates are: $\tau_M = 0.15$, $t_C = 0.20$ (solid line), $t_C = 0.30$ (dotted line), and $t_C = 0.40$ (gray line). The policy shock consists of $\tilde{\tau}_M = -0.01$ and $\tilde{t}_C = -\varepsilon\tilde{\tau}_M$.

between existing generations (represented by generation index $v < 0$) and future generations (represented by generation index $v = t \geqslant 0$), where the time at which the policy reform takes place is normalized to $t = 0$. The welfare effect for existing generations is defined as the change in expected lifetime utility at the time of the reform $d\Lambda^*(v, 0)$, whereas the welfare effect for future generations is defined as the change in expected lifetime utility evaluated at birth $d\Lambda^*(t, t)$. By log-linearizing (3.1), using (3.4a) and (3.5), we find the change in lifetime utility for all generations (Appendix 3.A.4):

$$d\Lambda^*(v,t) = \frac{\tilde{X}(v,t)}{\rho + \beta}. \tag{3.24}$$

3.5.2.1 Existing Generations

Existing generations are born before the implementation of the policy shock and thus have already accumulated financial assets. Equation (3.6) shows that full consumption is a fixed fraction of total wealth. Following Bovenberg (1993), the average welfare effect of the generations currently alive is given by:

$$(\rho + \beta) d\Lambda^*(0) = \left(1 - \frac{\beta}{\beta + r - \rho}\right) \frac{\tilde{A}(0)}{\omega_A} + \frac{\beta}{\beta + r - \rho} \frac{\tilde{H}(0)}{\omega_H},$$

where $\omega_H \equiv rH/Y$. Hence, the average welfare effect is a weighted average of the change in financial wealth and human capital of existing generations. The coordinated tax-tariff reform boosts financial wealth at the time of the policy change, because the increase in the value of land—due to a current and future reallocation of labor to the export sector—dominates the negative wealth effect of the fall in Tobin's q. Human capital is positively affected by an expansion of the informal sector—via the implicit income of informal workers—and a rise in lump-sum transfers and negatively by the drop in the wage bill of formal workers. In the benchmark scenario, human capital increases, reflecting the dominant effect of an increase in home production and lump-sum transfers.

Under the assumption that every existing generation has the same relative shares of equity and land in its portfolio, the welfare change for generation v is given by:

$$(\rho + \beta) d\Lambda^*(v, 0) = \left(1 - e^{(r-\rho)v}\right) \frac{\tilde{A}(0)}{\omega_A} + e^{(r-\rho)v} \frac{\tilde{H}(0)}{\omega_H}, \tag{3.25}$$

where $0 < e^{(r-\rho)v} < 1$ is the share of human wealth in the household's wealth portfolio, which is decreasing in the generation's age. For relevant parameters, we find that the reform increases both short-run financial wealth and human capital, where financial wealth rises by more than human capital. Old generations benefit to a larger extent from the reform than young existing generations as the share of financial assets in their wealth portfolio is larger.

3.5.2.2 Future Generations

Future generations are born without any financial assets, so that the change in their full consumption level at birth is fully determined by the change in human capital. Therefore, the change in lifetime utility of future generations is given by:

$$(\rho + \beta) d\Lambda^*(t,t) = \frac{\tilde{H}(t)}{\omega_H}.$$

The coordinated tax-tariff reform leads to a downward sloping time profile of human capital as a result of the dominant effect of declining profiles of both wages and formal employment.[21] Intuitively, future generations have a smaller capital stock to work with than existing generations and are therefore less productive. Hence, the change in lifetime utility for future generations is decreasing in the year of birth.

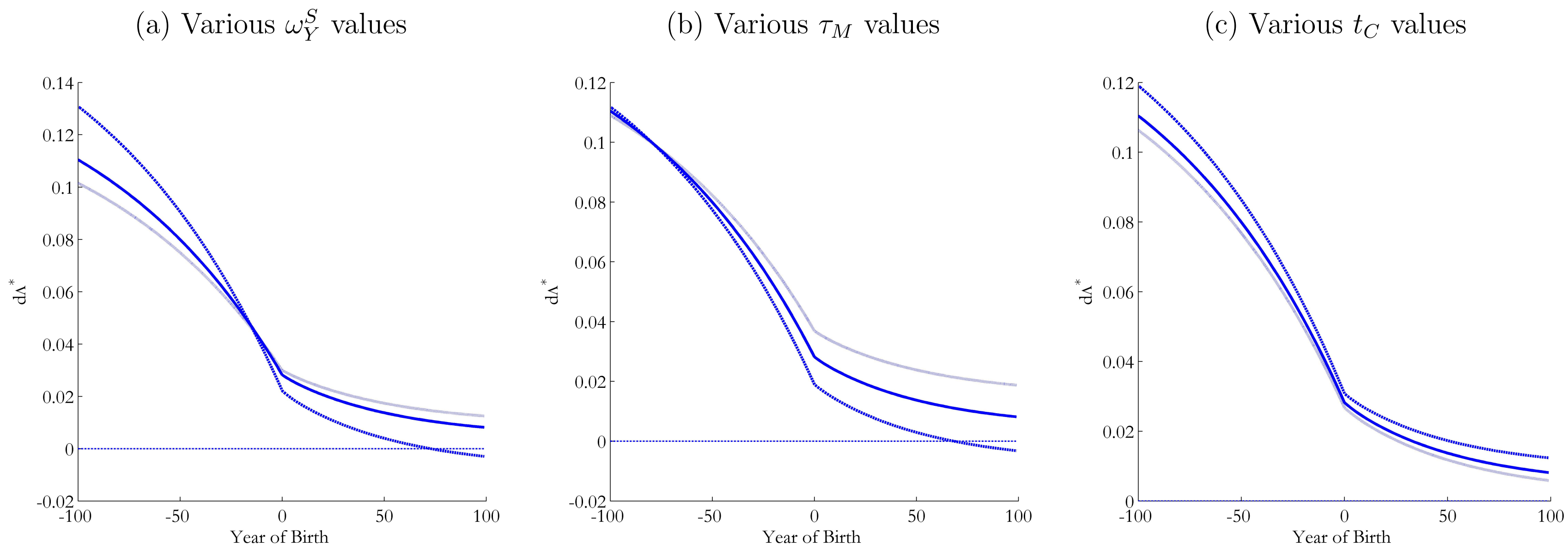
3.5.2.3 Welfare Profiles: Numerical Evidence

Figure 3.6 shows the intergenerational welfare profiles resulting from our benchmark calibration.[22] Because the initial distortions—and thus the welfare effects—depend on the GDP share of the informal sector and on the pre-existing tax and tariff rates, three different cases are considered. Panel (a) depicts the effect for various sizes of the informal sector, Panel (b) illustrates the effect for various initial import tariff rates and a given consumption tax rate, and Panel (c) shows the effect for various pre-existing consumption tax rates and a given tariff rate. A larger informal sector dampens the jump in financial wealth, but amplifies the jump in human capital. Therefore, it reduces welfare of old existing generations (who depend heavily on financial wealth) and benefits future generations (who

[21] In the calibrated model, the fall in the wage bill dominates the increase in home production and the change in lump-sum transfers.

[22] The downward sloping lines on the interval $[-100, 0]$ are only valid under the assumption that every existing generation has the same relative shares of capital and land in its asset portfolio. This assumption does not apply to Table 3.5, where we analyze the average welfare change for existing generations (cf. Bovenberg, 1993).

Figure 3.6: Intergenerational Welfare Profiles



Notes: In Panel (a) the pre-existing tax and tariff rates are set at their benchmark values. The relative sizes of the informal sector are $\omega_Y^S = 0.20$ (dotted line), $\omega_Y^S = 0.47$ (solid line), and $\omega_Y^S = 0.63$ (gray line). In Panel (b), the pre-existing tax and tariff rates are: $t_C = 0.125$, $\tau_M = 0.20$ (solid line), $\tau_M = 0.175$ (dotted line), and $\tau_M = 0.225$ (gray line). In Panel (c), the pre-existing tax and tariff rates are: $\tau_M = 0.20$, $t_C = 0.125$ (solid line), $t_C = 0.075$ (dotted line), and $t_C = 0.15$ (gray line). The welfare profiles of existing generations are valid under the assumption that every existing generation has the same relative share of capital and land in its asset portfolio. The policy shock consists of $\tilde{\tau}_M = -0.01$ and $\tilde{t}_C = -\varepsilon\tilde{\tau}_M$.

Table 3.5: Average Welfare Change for Existing Generations: Various Values of the Informal Sector and Pre-Existing Taxes

	$\tau_M = 0.175$			$\tau_M = 0.200$			$\tau_M = 0.225$		
ω_Y^S	$\tau_C = 0.075$	$\tau_C = 0.125$	$\tau_C = 0.175$	$\tau_C = 0.075$	$\tau_C = 0.125$	$\tau_C = 0.175$	$\tau_C = 0.075$	$\tau_C = 0.125$	$\tau_C = 0.175$
0.20	0.062	0.058	0.055	0.066	0.063	0.059	0.070	0.067	0.064
0.47	0.059	0.054	0.048	0.064	0.059	0.054	0.068	0.064	0.059
0.63	0.057	0.051	0.045	0.062	0.057	0.051	0.067	0.062	0.056

Notes: All parameters are set at their benchmark values. The policy shock consists of $\tilde{\tau}_M = -0.01$ and $\tilde{t}_C = -\varepsilon\tilde{\tau}_M$. The productivity index Ω_S takes on the values 0.60, 0.85, and 0.95 to generate ω_Y^S values of 0.20, 0.47, and 0.63, respectively.

only consume out of human capital). Increasing the initial import tariff rate (and thus the pre-existing import tariff distortion) positively affects the welfare change of most generations. However, the welfare change of old existing generations becomes smaller because the higher import tariff leads to a larger share of domestic capital in the aggregate wealth portfolio, which depresses the jump in financial wealth. As one would expect, increasing the initial consumption tax rate (and thus the consumption tax distortion) shifts down the welfare profile.

Table 3.5 presents the average welfare change of existing generations for different combinations of pre-existing tax and tariff rates and sizes of the informal sector. The welfare gain depends positively on the pre-existing tariff rate and negatively on the pre-existing consumption tax rate. Moreover, the size of the informal sector negatively affects the average welfare gain.

3.6 Conclusions

We have developed a dynamic micro-founded model of a small open developing economy with an informal sector to study the revenue, efficiency, and intergenerational welfare effects of a coordinated reform of tariffs and taxes. More specifically, we analyze a simple strategy of offsetting a cut in import tariffs by an increase in destination-based consumption taxes, so as to leave the consumer price index unchanged. Our model features both an informal and formal agricultural sector and a formal manufacturing sector. We derive analytically the allocation effects of the reform. To quantify the dynamic allocation and welfare effects, we simulate the model that is calibrated to match the characteristics of a typical small open developing economy.

We find that the reform strategy increases steady-state government revenue, imports, and exports. In addition, long-run economic activity in both the informal and formal agricultural sector expands at the expense of the import-competing manufacturing sector; however, informal agricultural output rises relatively more. Aggregate formal employment and output go down, more so in the long run than in the short run. The qualitative allocation effects for output and employment are robust to changes in the size of the informal sector. For plausible parameter values, efficiency improves. Intuitively, the reform alleviates the tariff distortion (yielding too much production and too little consumption of import substitutes) more than it exacerbates the consumption tax distortion (giving rise to excess home production). More specifically, lower tariff rates depress capital accumulation in the (at the margin) inefficient import-substitution sector and thus yield a larger welfare gain than in static models. Accordingly, we contribute to the academic literature by showing that ignoring dynamics in general, and capital accumulation in particular, may give rise to misleading policy conclusions. Moreover, we show that the welfare gain is unequally distributed across generations. Old existing generations benefit more than young and future generations, who may even become worse off if the pre-existing import tariff rate is low or the informal sector is relatively small.

Our study assumed frictionless labor and capital markets. Future research will focus on extending the model to include factor market imperfections. In addition, we will generalize the production structure and allow for intermediate inputs. Because the informal sector is hard to tax at the retail stage, developing countries often try to collect some revenue from this sector by using withholding taxes on (imported) intermediate inputs.

3.A Appendix

This Appendix sets out the solution procedure. It derives quasi-reduced forms, analyzes stability, and derives the comparative dynamics of a consumer-price neutral reform: $\tilde{t}_C = -\varepsilon\tilde{\tau}_M$.

3.A.1 Quasi-Reduced Forms

The model is log-linearized around an initial steady state in which $F(0) = 0$. Table 3.1 summarizes the model. A tilde ($\tilde{\ }$) denotes a relative change (e.g., $\tilde{X}(t) \equiv dX(t)/X$) for most variables. Exceptions are the following: (i) financial assets $A(t)$, $V_Z(t)$, and $F(t)$ and human capital $H(t)$, which are scaled by GDP and multiplied by r (e.g., $\tilde{A}(t) \equiv rdA(t)/Y$); (ii) lump-sum transfers $T(t)$, which are scaled by GDP only (e.g., $\tilde{T}(t) \equiv dT(t)/Y$); and (iii) tax and tariff rates, which are defined as $\tilde{t}_C \equiv dt_C/(1+t_C)$ and $\tilde{\tau}_M \equiv d\tau_M/(1+\tau_M)$. Time derivatives of variables are generally defined as $\dot{\tilde{X}} \equiv \dot{X}(t)/X$, except for $\dot{\tilde{A}}(t) \equiv r\dot{A}(t)/Y$, $\dot{\tilde{F}}(t) \equiv r\dot{F}(t)/Y$, and $\dot{\tilde{V}}_Z(t) \equiv r\dot{V}_Z(t)/Y$. We use the shares reported in Table 3.3. In the following, we will drop time subscripts.

We condense the production side of the model to quasi-reduced form expressions in the state variable $\tilde{K}$ and the policy variables $\tilde{t}_C$ and $\tilde{\tau}_M$ by solving (T1.07) and (T1.13) for the labor market equilibrium:

$$\begin{bmatrix} \omega_L^M & \omega_L^E & \omega_L^S & 0 \\ \alpha_M & 0 & 0 & 1 \\ 0 & \alpha_E & 0 & 1 \\ 0 & 0 & \alpha_S & 1 \end{bmatrix} \begin{bmatrix} \tilde{L}_M \\ \tilde{L}_E \\ \tilde{L}_S \\ \tilde{w} \end{bmatrix} = \begin{bmatrix} 0 \\ \tilde{\tau}_M + \alpha_M\tilde{K} \\ 0 \\ \tilde{t}_C \end{bmatrix}, \tag{A.3.1}$$

where the determinant of the coefficient matrix Ω on the left-hand side of (A.3.1) is given by:

$$|\Omega| = \alpha_M\alpha_E\omega_L^S + \alpha_S\alpha_E\omega_L^M + \alpha_S\alpha_M\omega_L^E. \tag{A.3.2}$$

Solving the system (A.3.1), we find the following expressions characterizing sectoral labor market equilibrium:

$$\tilde{L}_M = \frac{\alpha_E\omega_L^S + \alpha_S\omega_L^E}{|\Omega|}\tilde{\tau}_M + \frac{\alpha_M\left(\alpha_E\omega_L^S + \alpha_S\omega_L^E\right)}{|\Omega|}\tilde{K} - \frac{\alpha_E\omega_L^S}{|\Omega|}\tilde{t}_C, \tag{A.3.3}$$

$$\tilde{L}_E = -\frac{\alpha_S\omega_L^M}{|\Omega|}\tilde{\tau}_M - \frac{\alpha_M\alpha_S\omega_L^M}{|\Omega|}\tilde{K} - \frac{\alpha_M\omega_L^S}{|\Omega|}\tilde{t}_C, \tag{A.3.4}$$

$$\tilde{L}_S = -\frac{\alpha_E \omega_L^M}{|\Omega|}\tilde{\tau}_M - \frac{\alpha_M \alpha_E \omega_L^M}{|\Omega|}\tilde{K} + \frac{\alpha_E \omega_L^M + \alpha_M \omega_L^E}{|\Omega|}\tilde{t}_C, \tag{A.3.5}$$

$$\tilde{w} = \frac{\alpha_S \alpha_E \omega_L^M}{|\Omega|}\tilde{\tau}_M + \frac{\alpha_M \alpha_S \alpha_E \omega_L^M}{|\Omega|}\tilde{K} + \frac{\alpha_M \alpha_E \omega_L^S}{|\Omega|}\tilde{t}_C. \tag{A.3.6}$$

We derive $\omega_L^F \tilde{L}_M = \omega_L^S \tilde{L}_S$ from (T1.13), where $\omega_L^F \equiv \omega_L^E + \omega_L^M$. By substituting this result into (T1.07), we derive the aggregate labor supply curve for the formal sector:

$$\tilde{L}_F = \frac{\omega_L^S}{\omega_L^F}\frac{1}{\alpha_S}(\tilde{w} - \tilde{t}_C). \tag{A.3.7}$$

The aggregate labor demand curve for the formal sector is obtained by substituting (T1.07) into $\omega_L^F \tilde{L}_F = \omega_L^E \tilde{L}_E + \omega_L^M \tilde{L}_M$:

$$\omega_L^F \tilde{L}_F = -\left(\frac{\omega_L^E}{\alpha_E} + \frac{\omega_L^M}{\alpha_M}\right)\tilde{w} + \omega_L^M \tilde{K} + \frac{\omega_L^M}{\alpha_M}\tilde{\tau}_M. \tag{A.3.8}$$

By using (T1.14)–(T1.17) and (T1.12), we can simplify the consumption side of the model to quasi-reduced form expressions, including as arguments the non-predetermined variable $\tilde{X}$, the state variable $\tilde{K}$, and the policy variables $\tilde{t}_C$ and $\tilde{\tau}_M$:

$$\tilde{C}_M = \tilde{X} - \tilde{t}_C - \tilde{\tau}_M, \tag{A.3.9}$$

$$\begin{aligned}\tilde{C}_E = {} & \frac{(1-\varepsilon)\omega_X}{\omega_C^E}\tilde{X} - \left[\frac{(1-\varepsilon)\omega_X}{\omega_C^E} + \frac{\omega_L^S}{\omega_C^E}\frac{(\alpha_E \omega_L^M + \alpha_M \omega_L^E)}{|\Omega|}\right]\tilde{t}_C \\ & + \frac{\omega_C^S}{\omega_C^E}\frac{(1-\alpha_S)\alpha_E \omega_L^M}{|\Omega|}\tilde{\tau}_M + \frac{\omega_L^S}{\omega_C^E}\frac{\alpha_M \alpha_E \omega_L^M}{|\Omega|}\tilde{K}.\end{aligned} \tag{A.3.10}$$

By substituting (T1.10), (A.3.3), (A.3.9), and (A.3.10) into (T1.18), we find the quasi-reduced form expression for government revenue:

$$\tilde{T} = \beta_K \tilde{K} + \beta_X \tilde{X} + \beta_M \tilde{\tau}_M + \beta_C \tilde{t}_C, \tag{A.3.11}$$

where β_K and β_X capture pure tax and tariff base effects, whereas β_C and β_M contain a combination of tax and tariff rate and base effects:

$$\begin{aligned}\beta_C &\equiv \eta\omega_X - \omega_L^S\left[\frac{1}{1-\alpha_S} + \frac{\tau_M \omega_L^M \alpha_E}{(1+\tau_M)\,|\Omega|} - \frac{t_C(\alpha_E \omega_L^M + \alpha_M \omega_L^E)}{(1+t_C)\,|\Omega|}\right], \\ \beta_M &\equiv -\omega_L^M\left[\frac{1}{1-\alpha_M} + \frac{\alpha_S \tau_M \omega_L^E}{(1+\tau_M)\,|\Omega|} + \frac{\alpha_E \varepsilon(t_C - \tau_M)\omega_L^S \omega_X}{1+t_C}\right], \\ \beta_X &\equiv (1-\eta)\omega_X > 0, \\ \beta_K &\equiv \frac{\alpha_M \omega_L^M}{|\Omega|}\left[\frac{t_C \omega_L^S(1-\alpha_E)}{1+t_C} - \frac{\tau_M[\alpha_E(\omega_L^S + \alpha_S \omega_L^M) + \alpha_S \omega_L^E]}{(1-\alpha_M)(1+\tau_M)}\right].\end{aligned}$$

3.A.2 Investment System

3.A.2.1 Stability and Long-Run Effects

The investment system (3.16) is obtained by substituting (T1.09), (T1.10), and the quasi-reduced form equation (A.3.3) into (T1.01) and (T1.02). The system features one predetermined variable $\tilde{K}$ and one non-predetermined variable $\tilde{q}$. The determinant of the first coefficient matrix Δ^I on the right-hand side of (3.16) is given by:

$$\left|\Delta^I\right| = -\delta_{12}\delta_{21} < 0. \tag{A.3.12}$$

The eigenvalues of Δ^I are given by:

$$-h_1^* = \frac{1}{2}\left(r - \sqrt{r^2 - 4\left|\Delta^I\right|}\right) < 0, \qquad r_1^* = h_1^* + r > 0. \tag{A.3.13}$$

Because there is one positive (unstable) eigenvalue and one negative (stable) eigenvalue, the model has a unique and saddle-point stable steady state.

The long-run effects can be derived by evaluating (3.16) in the steady state:

$$\begin{bmatrix} 0 & \delta_{12} \\ \delta_{21} & r \end{bmatrix} \begin{bmatrix} \tilde{K}(\infty) \\ \tilde{q}(\infty) \end{bmatrix} = \begin{bmatrix} 0 \\ \lambda_q + \varepsilon\gamma_q \end{bmatrix} \tilde{\tau}_M, \tag{A.3.14}$$

where we used the consumer-price neutrality of the policy reform. By solving this system, we find the long-run effects:

$$\tilde{K}(\infty) = \frac{\lambda_q + \varepsilon\gamma_q}{\delta_{21}}\tilde{\tau}_M, \tag{A.3.15}$$

$$\tilde{q}(\infty) = 0. \tag{A.3.16}$$

3.A.2.2 Initial Effect and Transitional Dynamics

We use the Laplace transform method of Judd (1982) to derive analytical expressions for the transitional dynamics of the model. The Laplace transform is defined as $\mathcal{L}\{x, s\} \equiv \int_0^\infty x(t)e^{-st}dt$, where s represents the discount rate and $\mathcal{L}$ is the Laplace transform operator. By taking the Laplace transform of (3.16)—and noting that $\tilde{K}(0) = 0$—we find:

$$\Lambda^I(s) \begin{bmatrix} \mathcal{L}\{\tilde{K}, s\} \\ \mathcal{L}\{\tilde{q}, s\} \end{bmatrix} = \begin{bmatrix} 0 \\ \tilde{q}(0) - (\lambda_q + \varepsilon\gamma_q)\mathcal{L}\{\tilde{\tau}_M, s\} \end{bmatrix}, \tag{A.3.17}$$

where $\Lambda^I(s) \equiv sI - \Delta^I$. We premultiply both sides of (A.3.17) by $\Lambda^I(s)^{-1}$ to get:

$$(s + h_1^*) \begin{bmatrix} \mathcal{L}\{\tilde{K}, s\} \\ \mathcal{L}\{\tilde{q}, s\} \end{bmatrix} = \frac{\operatorname{adj} \Lambda^I(s)}{s - r_1^*} \begin{bmatrix} 0 \\ \tilde{q}(0) - (\lambda_q + \varepsilon\gamma_q)\mathcal{L}\{\tilde{\tau}_M, s\} \end{bmatrix}, \quad \text{(A.3.18)}$$

where we used Cramer's rule:

$$\Lambda^I(s)^{-1} = \frac{\operatorname{adj} \Lambda^I(s)}{|\Lambda^I(s)|} = \frac{1}{(s - r_1^*)(s + h_1^*)} \operatorname{adj} \Lambda^I(s). \quad \text{(A.3.19)}$$

The adjoint matrix of $\Lambda^I(s)$ is given by:

$$\operatorname{adj} \Lambda^I(s) \equiv \begin{bmatrix} s - r & \delta_{12} \\ \delta_{21} & s \end{bmatrix}. \quad \text{(A.3.20)}$$

By eliminating the positive root that violates the transversality condition, we find the following condition:

$$\operatorname{adj} \Lambda^I(r_1^*) \begin{bmatrix} 0 \\ \tilde{q}(0) - (\lambda_q + \varepsilon\gamma_q)\mathcal{L}\{\tilde{\tau}_M, r_1^*\} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \quad \text{(A.3.21)}$$

We examine an unanticipated and permanent shock to the system, so that $\mathcal{L}\{\tilde{\tau}_M, s\} = \tilde{\tau}_M/s$. Consequently, the jump in Tobin's q is given by:

$$\tilde{q}(0) = \frac{\lambda_q + \varepsilon\gamma_q}{r_1^*}\tilde{\tau}_M. \quad \text{(A.3.22)}$$

By taking the inverse Laplace transform of the first and second row of (A.3.17) and imposing (A.3.22), we obtain (3.18)–(3.19) as reported in the main text.

3.A.3 Savings System

3.A.3.1 Stability and Long-Run Effects

The savings system (3.17) is obtained by substituting (T1.12) and the quasi-reduced form equations (A.3.3)–(A.3.6), and (A.3.11) into (T1.03) and (T1.04); it features one predetermined variable $\tilde{X}$ and one non-predetermined variable $\tilde{A}$. The determinant of the first coefficient matrix Δ^S on the right-hand side is given by:

$$\left|\Delta^S\right| = r(r - \rho)\left(1 - \eta\frac{\omega_X}{\omega_A}\right) = -(r + \eta\beta)(\rho - r + \eta\beta) - \eta(1 - \eta)\beta^2, \quad \text{(A.3.23)}$$

where we have used (T1.03). The system has a unique and saddle-path stable steady state if $\left|\Delta^S\right| < 0$, in which case there is one positive (unstable) and one negative (stable) real root. It follows from (A.3.23) that $\left|\Delta^S\right| < 0$ if $r < \rho + \eta\beta$. The eigenvalues of Δ^S are given by:

$$-h_2^* = \frac{1}{2}\left(2r - \rho - \sqrt{(2r-\rho)^2 - 4\left|\Delta^S\right|}\right) < 0, \qquad r_2^* = h_2^* + r > 0. \tag{A.3.24}$$

The long-run effects of the reform are obtained by evaluating (3.17) in steady state:

$$\begin{bmatrix} r-\rho & -\frac{r-\rho}{\omega_A} \\ -r\eta\omega_X & r \end{bmatrix} \begin{bmatrix} \tilde{X}(\infty) \\ \tilde{A}(\infty) \end{bmatrix} = \begin{bmatrix} 0 \\ -\kappa_A \end{bmatrix} \tilde{K}(\infty) + \begin{bmatrix} 0 \\ -(\lambda_A - \varepsilon\gamma_A) \end{bmatrix} \tilde{\tau}_M, \tag{A.3.25}$$

where the shock vectors are given by:

$$\kappa_A \equiv r\left[\frac{(\omega_L^M + \omega_L^E)\alpha_M\alpha_E\alpha_S\omega_L^M}{|\Omega|} + \beta_K\right], \tag{A.3.26}$$

$$\lambda_A \equiv r\left[\frac{(\omega_L^M + \omega_L^E)\alpha_E\alpha_S\omega_L^M}{|\Omega|} + \beta_M\right], \tag{A.3.27}$$

$$\gamma_A \equiv r\left[\frac{(\omega_L^M + \omega_L^E)\alpha_M\alpha_E\omega_L^S}{|\Omega|} + \frac{\omega_L^S}{1-\alpha_S} + \beta_C\right], \tag{A.3.28}$$

and we have used the consumer-price neutrality of the policy reform. Solving (A.3.25), we find the long-run effects:

$$\tilde{X}(\infty) = \frac{1}{\omega_A}\tilde{A}(\infty) = \frac{r(r-\rho)\omega_I\left[\kappa_A(\varepsilon\gamma_q + \lambda_q) - \delta_{21}(\varepsilon\gamma_A - \lambda_A)\right]}{\chi_K\omega_K\omega_A\left|\Delta^I\right|\left|\Delta^S\right|}\tilde{\tau}_M. \tag{A.3.29}$$

3.A.3.2 Proof of Signs

This section first gives three sufficient (but not necessary) conditions for $\varepsilon\gamma_A - \lambda_A > 0$. Second, it gives two sufficient (but not necessary) conditions for a positive jump in aggregate financial wealth. After dividing by r and simplifying, $\varepsilon\gamma_A - \lambda_A$ can be written as:

$$\begin{aligned}\frac{\varepsilon\gamma_A - \lambda_A}{r} &= \omega_L^M\left[\frac{1}{1-\alpha_M} - \frac{(\omega_L^E + \omega_L^M)\alpha_E\alpha_S}{|\Omega|}\right] \\ &+ \frac{\tau_M}{1+\tau_M}\frac{\omega_L^M}{|\Omega|}\left(\alpha_S\omega_L^E - \varepsilon\alpha_E\omega_L^S\right) \\ &+ \frac{\omega_X\varepsilon\left[\eta(1+t_C) - \omega_L^S\omega_L^M(\tau_M - t_C)\right]|\Omega|}{(1+t_C)\,|\Omega|} \\ &+ \frac{\varepsilon(\omega_L^M + \omega_L^E)\omega_L^S\alpha_M\alpha_E}{|\Omega|} + \frac{\varepsilon t_C\omega_L^S\left(\alpha_E\omega_L^M + \alpha_M\omega_L^E\right)}{(1+t_C)\,|\Omega|}.\end{aligned}$$

The terms between brackets in the first, second, and third line are positive if $\alpha_E \geqslant \alpha_M$, $\varepsilon\omega_L^S/\omega_L^E < \alpha_S/\alpha_E$, and $(1+\tau_M)(\tau_M - t_C)\omega_L^M\omega_L^S < 1 + (1-\varepsilon)\tau_M$, respectively. These three conditions are easily satisfied for plausible parameter values.

Two sufficient conditions for a positive jump in aggregate financial wealth are:

$$\frac{\omega_L^E}{\omega_L^M}\frac{1}{1+t_C}\frac{1-\alpha_E}{\alpha_E}h_1^* > r, \tag{A.3.30}$$

$$\varepsilon\frac{\omega_L^S}{\omega_L^M} < \frac{\alpha_S}{\alpha_M}. \tag{A.3.31}$$

3.A.3.3 Initial Effect and Transitional Dynamics

By taking the Laplace transform of (3.17) and noting that $\tilde{A}(0) = \tilde{V}_Z(0) + \omega_K\tilde{q}(0)$, we find:

$$\Lambda^S(s)\begin{bmatrix}\mathcal{L}\{\tilde{X},s\}\\ \mathcal{L}\{\tilde{A},s\}\end{bmatrix} = \begin{bmatrix}\tilde{X}(0)\\ \omega_K\tilde{q}(0) + \tilde{V}_Z(0) - (\varepsilon\gamma_A - \lambda_A)\mathcal{L}\{\tilde{\tau}_M,s\} + \frac{\delta_{41}\delta_{12}}{s(s+h_1^*)}\tilde{q}(0)\end{bmatrix}, \tag{A.3.32}$$

where $\Lambda^S(s) \equiv sI - \Delta^S$. We premultiply both sides of (A.3.32) by $\Lambda^S(s)^{-1}$, use Cramer's rule, and impose the shock to be unanticipated and permanent ($\mathcal{L}\{\tilde{\tau}_M,s\} = \tilde{\tau}_M/s$) to get:

$$(s+h_2^*)\begin{bmatrix}\mathcal{L}\{\tilde{X},s\}\\ \mathcal{L}\{\tilde{A},s\}\end{bmatrix} = \frac{\operatorname{adj}\Lambda^S(s)}{s-r_2^*}\begin{bmatrix}\tilde{X}(0)\\ \omega_K\tilde{q}(0) + \tilde{V}_Z(0) - (\varepsilon\gamma_A - \lambda_A)\frac{\tilde{\tau}_M}{s} + \frac{\delta_{41}\delta_{12}}{s(s+h_1^*)}\tilde{q}(0)\end{bmatrix}. \tag{A.3.33}$$

The adjoint matrix of $\Lambda^S(s)$ is given by:

$$\operatorname{adj}\Lambda^S(s) \equiv \begin{bmatrix} s-r & -\frac{r-\rho}{\omega_A}\\ -r\eta\omega_X & s-(r-\rho)\end{bmatrix}. \tag{A.3.34}$$

Eliminating the positive (unstable) root that violates the transversality condition for firms in the import substitution sector leads to the following condition:

$$\operatorname{adj}\Lambda^S(r_2^*)\begin{bmatrix}\tilde{X}(0)\\ \omega_K\tilde{q}(0) + \tilde{V}_Z(0) - (\varepsilon\gamma_A - \lambda_A)\frac{\tilde{\tau}_M}{r_2^*} + \frac{\kappa_A\delta_{12}}{r_2^*(r_2^*+h_1^*)}\tilde{q}(0)\end{bmatrix} = \begin{bmatrix}0\\0\end{bmatrix}. \tag{A.3.35}$$

Consequently, the jump in full consumption is given by:

$$\tilde{X}(0) = \frac{h_2^* + \rho}{r\eta\omega_X} \left[\left(\omega_K + \frac{r\omega_I \kappa_A}{\chi_K \omega_K r_2^* (r_2^* + h_1^*)} \right) \tilde{q}(0) + \tilde{V}_Z(0) - \frac{\varepsilon\gamma_A - \lambda_A}{r_2^*} \tilde{\tau}_M \right]. \tag{A.3.36}$$

By substituting the jump in the value of land that is derived in Appendix 3.A.3.4, equation (3.21) in the main text is obtained. We define the following temporary transition terms:

$$\mathbf{T}_1(h_i^*, t) \equiv e^{-h_i^* t}, \quad i = \{1, 2\}, \tag{A.3.37}$$

$$\mathbf{T}_2(h_1^*, h_1^*, t) \equiv \frac{1}{h_1^* h_2^*} + \frac{e^{-h_1^* t}}{h_1^*(h_1^* - h_2^*)} - \frac{e^{-h_2^* t}}{h_2^*(h_1^* - h_2^*)}, \tag{A.3.38}$$

$$\mathbf{T}_3(h_1^*, h_2^*, t) \equiv \frac{d\mathbf{T}_2(h_1^*, h_2^*, t)}{dt} = \frac{e^{-h_2^* t}}{h_1^* - h_2^*} - \frac{e^{-h_1^* t}}{h_1^* - h_2^*}. \tag{A.3.39}$$

By taking the inverse Laplace transform of the first row of (A.3.32), and imposing (A.3.35), we obtain the transition path for full consumption:

$$\begin{aligned}\tilde{X}(t) = &\ \mathbf{T}_1(h_2^*, t)\tilde{X}(0) - [1 - \mathbf{T}_1(h_2^*, t)] \frac{\delta_{12}\delta_{21}(r-\rho)(\varepsilon\gamma_A - \lambda_A)}{\omega_A |\Delta^I| |\Delta^S|} \tilde{\tau}_M \\ &+ \left[\mathbf{T}_2(h_1^*, h_2^*, t) + \frac{\mathbf{T}_3(h_1^*, h_2^*, t)}{r_2^* + h_1^*} \right] \frac{\delta_{12}(r-\rho)\kappa_A (\lambda_q + \varepsilon\gamma_q)}{\omega_A r_1^* r_2^*} \tilde{\tau}_M.\end{aligned}$$

Similarly, the transition path for financial wealth is obtained by taking the inverse Laplace transform of the second row of (A.3.32) and imposing (A.3.35):

$$\begin{aligned}\tilde{A}(t) = &\ \mathbf{T}_1(h_2^*, t) \left[\omega_K \tilde{q}(0) + \tilde{V}_Z(0) \right] + [1 - \mathbf{T}_1(h_2^*, t)] \frac{\delta_{12}\delta_{21}(r-\rho)(\lambda_A - \varepsilon\gamma_A)}{|\Delta^I| |\Delta^S|} \tilde{\tau}_M \\ &+ \mathbf{T}_2(h_1^*, h_2^*, t) \frac{\delta_{12}(r-\rho)\kappa_A(\lambda_q + \varepsilon\gamma_q)}{r_1^* r_2^*} \tilde{\tau}_M.\end{aligned} \tag{A.3.40}$$

3.A.3.4 Value of Land

By substituting (T1.08) and (A.3.4) into the Laplace transform of (T1.06), we obtain:

$$\begin{aligned}\mathcal{L}\{\tilde{V}_Z, s\} = &\ \frac{1}{s-r}\tilde{V}_Z(0) + \frac{1}{s(s-r)} \frac{r\omega_Z(1-\alpha_E)(\alpha_S\omega_L^M - \varepsilon\alpha_M\omega_L^S)}{|\Omega|} \tilde{\tau}_M \\ &+ \frac{1}{s-r} \left(\frac{1}{s} - \frac{1}{h_1^* + s} \right) \frac{r\omega_Z(1-\alpha_E)\alpha_M\alpha_S\omega_L^M}{|\Omega|} \frac{\lambda_q + \varepsilon\gamma_q}{\delta_{21}} \tilde{\tau}_M.\end{aligned} \tag{A.3.41}$$

Imposing the transversality condition for the aggregate household sector gives the jump in the value of land:

$$\tilde{V}_Z(0) = -\frac{\omega_Z(1-\alpha_E)(\alpha_S\omega_L^M - \varepsilon\alpha_M\omega_L^S)}{|\Omega|}\tilde{\tau}_M - \frac{h_1^*}{h_1^*+r}\frac{\omega_Z(1-\alpha_E)\alpha_M\alpha_S\omega_L^M}{|\Omega|}\frac{\lambda_q+\varepsilon\gamma_q}{\delta_{21}}\tilde{\tau}_M. \quad \text{(A.3.42)}$$

To obtain the transitional dynamics for the value of land, we take the inverse Laplace transform of (A.3.41) and substitute (A.3.42) for $\tilde{V}_Z(0)$:

$$\tilde{V}_Z(t) = -\frac{\omega_Z(1-\alpha_E)(\alpha_S\omega_L^M - \varepsilon\alpha_M\omega_L^S)}{|\Omega|}\tilde{\tau}_M + \left[\frac{\mathbf{T}_1(h_1^*,t)}{h_1^*+r} - \frac{1}{r}\right]\frac{r\omega_Z(1-\alpha_E)\alpha_M\alpha_S\omega_L^M}{|\Omega|}\frac{\lambda_q+\varepsilon\gamma_q}{\delta_{21}}\tilde{\tau}_M. \quad \text{(A.3.43)}$$

3.A.4 Welfare Analysis

By substituting (3.4a) and (3.5) into the utility functional $\Lambda(v,t)$, an expression for indirect utility is obtained:

$$\Lambda^*(v,t) = \int_t^\infty \left[\ln X(v,z) - \ln p_C(v,z)\right] e^{-(\rho+\beta)(z-t)}dz. \quad \text{(A.3.44)}$$

It follows from (3.4c) that full consumption on the optimal path obeys $X(v,z) = X(v,t)e^{(r-\rho)(z-t)}$. We substitute this into (A.3.44) and solve the resulting integral to get:

$$\Lambda^*(v,t) = \frac{X(v,t)}{\rho+\beta} + \frac{1}{(\rho+\beta)^2} - \int_t^\infty \ln p_C(z)e^{-(\rho+\beta)(z-t)}dz. \quad \text{(A.3.45)}$$

The change in utility (3.24) follows from differentiating (A.3.45).

3.A.4.1 Existing Generations ($v < 0$)

Existing generations are born before the policy shock occurs and have already accumulated financial assets. Their level of full consumption at the time of the shock ($t = 0$) is given by (3.6), so that we find:

$$\tilde{X}(v,0) = [1-\psi(v,0)]\frac{\tilde{A}(v,0)}{\omega_A} + \psi(v,0)\frac{\tilde{H}(0)}{\omega_H}, \quad \psi(v,0) \equiv \frac{H(0)}{A(v,0)+H(0)}. \quad \text{(A.3.46)}$$

The aggregate counterpart of (3.6) can be used to get:

$$\tilde{H}(0) = \frac{1}{\rho+\beta}r\omega_X\tilde{X}(0) - \tilde{A}(0). \quad \text{(A.3.47)}$$

Assuming that the economy was in the same steady-state equilibrium before the shock occurred, we have $X(v,0) = X(v,v)e^{-(r-\rho)v}$. Combining this with (3.6) yields:

$$\begin{aligned}(\rho+\beta)\left[A(v,0)+H(0)\right] &= X(v,v)e^{-(r-\rho)v} \\ &= (\rho+\beta)H(0)e^{-(r-\rho)v} \Rightarrow \psi(v,0) = e^{(r-\rho)v},\end{aligned} \tag{A.3.48}$$

where we have used $A(v,v) = 0$ and $H(v) = H(0)$ for the second equality. Under the assumption that the relative share of capital and land in the wealth portfolio is the same for all existing generations, we have $\tilde{A}(v,0) = \tilde{A}(0)$. By substituting this equality and (A.3.48) into (A.3.46), we obtain:

$$\tilde{X}(v,0) = \left(1 - e^{(r-\rho)v}\right)\frac{\tilde{A}(0)}{\omega_A} + e^{(r-\rho)v}\frac{\tilde{H}(0)}{\omega_H}. \tag{A.3.49}$$

The change in welfare of existing generations (3.25) follows from combining (3.24) and (A.3.49).

3.A.4.2 Future Generations ($v = t \geqslant 0$)

Future generations are born without financial capital $A(v,v) = 0$, implying that $\psi(v,t) = 1$ for $v \geqslant t$. Substituting this in (3.25), we obtain the change in welfare of future generations:

$$d\Lambda^*(t,t) = \frac{1}{\rho+\beta}\frac{\tilde{H}(t)}{\omega_H}. \tag{A.3.50}$$

Chapter 4

Resource Extraction, Backstop Technologies, and Endogenous Growth

"Let Pharaoh do this, and let him appoint officers over the land, to collect one-fifth of the produce of the land of Egypt in the seven plentiful years. And let them gather all the food of those good years that are coming, and store up grain under the authority of Pharaoh, and let them keep food in the cities. Then that food shall be as a reserve for the land for the seven years of famine which shall be in the land of Egypt, that the land may not perish during the famine."

— Genesis 41:34-36

4.1 Introduction

Economic growth and natural resource use have been intrinsically linked throughout history. While in the Malthusian era land improvement and expansions allowed for population increases, in the modern economy era coal and later oil made the steady growth of manufactured output per capita possible. Since fossil resources have seemed so abundant for most of the time since the (second) industrial revolution, our theories of growth could safely ignore the role of resources and focus on capital investment and technical change. However, fossil resources are non-renewable and at some point resource scarcity will be likely to restrict growth. The limited availability of our main current sources of energy gives rise to two possible scenarios: either we need to gradually reduce energy use and prevent sudden declines in energy supply, or substitutes for fossil energy need to be introduced. Both scenarios involve costs and the natural question is to what extend growth will be influenced. In particular, the question is how the engine of growth in our modern economies, namely investment and innovation, will be affected. The reduction in energy use is a direct drag on growth and reduces the market for innovations. A transition to alternative energies implies a shift to higher cost energy and might also leave less room for innovation.

To answer this question, we propose a model in which growth is driven by R&D and that integrates the use of energy from potentially two sources: non-renewable (fossil) resources that can be extracted without cost from the earth's crust and a form of energy that is produced by using renewable resource like solar energy or wind. Nordhaus (1973) was the first one to introduce such a substitute technology that is not constrained by exhaustibility, which he called a 'backstop technology'. Examples of already available backstop technologies for natural resources are nuclear fusion, solar energy, and wind energy. Backstop technologies are often not yet competitive enough to be implemented on a large scale (Chakravorty, Roumasset, and Tse, 1997; Gerlagh and Lise, 2003; IPCC, 2012). We contribute to the literature by studying the effects of the availability of a backstop technology on the rate of technological progress and the resource extraction path in an analytically tractable, general equilibrium model.

Our main findings are, first, that the economy experiences different regimes of energy generation: a resource regime and a backstop regime. Moreover, a regime of simultaneous use may exist, even without imposing the convexities in backstop production or resource extraction costs that are normally required for obtaining this result. Second, the time profile of the rate of technological progress is non-monotonic, whereas it would be monotonically decreasing without the backstop technology available. Third, technological progress is faster during the entire resource regime than it would be without the backstop technology. Finally, the resource extraction path does no longer necessarily become downward sloping eventually (as it would without the backstop technology). We provide conditions under which the development of extraction is upward-sloping or downward-sloping until exhaustion, or exhibits an internal resource extraction peak, usually referred to as 'peak-oil'. The shape of the time path depends crucially on the elasticity of substitution between energy and man-made inputs.

The first building block of our analysis is the so-called Dasgupta-Heal-Solow-Stiglitz (DHSS) model. The DHSS model integrates non-renewable resources into the neoclassical exogenous growth framework, and consists of the seminal contributions of Dasgupta and Heal (1974), Solow 1974a; 1974b, and Stiglitz 1974a; 1974b.[1] Some important lessons from the DHSS model are that a necessary resource stock should not be exhausted in finite time, that a positive constant consumption level can be sustained forever if the elasticity of substitution between the resource and man-made inputs is at least unity, if the output elasticity of the resource is not larger than that of physical capital, and if physical capital does not depreciate, or if the rate of exogenous technological progress is large enough (Solow, 1974b; Stiglitz, 1974a).[2] Moreover, for the special case of Cobb-Douglas production and a constant positive pure rate of time preference, Dasgupta and Heal (1974) show that the optimal time path of resource extraction is downward sloping over the entire time horizon.

Although backstop technologies are not an integrated feature of the DHSS model, some of the early studies do take the existence of substitutes for the non-renewable resource into account. Dasgupta and Heal (1974) and Dasgupta and Stiglitz (1981) allow for the invention of a backstop technology, which occurs each period with an exogenously given probability. The backstop invention probability is shown to have important consequences for resource prices and extraction paths. Kamien and Schwartz (1978) introduce the possibility of undertaking R&D to affect the probability of invention. In partial equilibrium settings, Hoel (1978) and Stiglitz and Dasgupta (1982) assume that a backstop technology already exists. They show that the relative price of the resource compared to the backstop technology increases over time and the backstop is adapted once prices are equalized. Both studies are concerned with the impact of different market structures on the timing of backstop technology adoption and the development of extraction and the resource price over time.

In the neoclassical models discussed so far, gradual technological progress was either absent or exogenous. Barbier (1999) was one of the first to study the role of endogenous technological change in alleviating resource scarcity. Scholz and Ziemes (1999) investigate the effect of monopolistic competition on steady

[1]Recently, Benchekroun and Withagen (2011) have developed a technique to calculate the closed form solution to the DHSS model.

[2]As noted in Chapter 1, a natural resource is defined to be 'necessary' if production is zero without input of the resource (Dasgupta and Heal, 1979).

state growth in a model with a necessary non-renewable resource. More recently, Bretschger and Smulders (2012) explore the consequences of poor input substitution possibilities and induced structural change for long-run growth prospects in a multi-sector economy. These three endogenous growth models, however, ignore the existence of a backstop technology for the natural resource. Tsur and Zemel (2003) fill this gap in the literature, by introducing R&D directed at a backstop technology. In their model, accumulation of knowledge gradually decreases the per unit cost of the backstop technology. Alternatively, Chakravorty, Leach, and Moreaux (2012) assume that per unit costs of the backstop technology decrease over time through learning by doing. The analyses of Tsur and Zemel (2003) and Chakravorty, Leach, and Moreaux (2012) are both casted in a partial equilibrium framework.

Accordingly, the existing literature on non-renewable resources in which technological progress is explained endogenously appears to suffer from a dichotomy: either backstop technologies or general equilibrium effects are being ignored. A synthesis of both strands of the literature is, however, desirable and likely to generate new insights (Valente, 2011). After all, contrary to the presumption in the partial equilibrium literature that imposes a fixed resource demand function, output growth and biased technological change both affect the demand for the resource, which should be taken into account.

There are three notable exceptions that are not subject to the dichotomy criticism. First, Tsur and Zemel (2005) develop a general equilibrium model where the unit costs of the backstop technology decrease as a result of R&D. The focus of this study, however, is on initial conditions that matter for long-run growth and the characteristics of an optimal R&D program. Moreover, R&D is only possible in the backstop sector, so that effects on aggregate technological progress cannot be addressed. Second, Tahvonen and Salo (2001) study the transition between renewable and non-renewable resource in general equilibrium. In their model, however, technological change results from learning-by-doing and does not come from intentional investments (R&D). Moreover, they resort to a Cobb-Douglas specification for final output, thereby ignoring poor substitution between resources and man-made inputs. Finally, Valente (2011) constructs a general equilibrium model in which the social planner optimally chooses whether and when to abandon the traditional resource-based technology in favor of the backstop technology. The differences with our analysis are that Valente (2011) (i) *a priori* prohibits simultaneous use of both technologies, (ii) ignores poor input substitution by imposing

Cobb-Douglas production, (iii) assumes a costless endowment of the backstop technology, and (iv) derives the social optimum instead of the decentralized market equilibrium. Moreover, his focus on the optimal timing of backstop technology adoption and on the optimal jumps in output and consumption at the regime switching instant is different from ours.

In this chapter, we develop a general equilibrium, endogenous growth model in which final output is produced with intermediate goods and energy. The production of intermediate goods requires labor. Energy is derived from a non-renewable natural resource that can be extracted at zero costs, or generated by a backstop technology. The elasticity of substitution between energy and intermediate goods is assumed to be smaller than unity. Technological progress in the model is driven by labor allocated to R&D directed at the invention of new intermediate goods. We assume knowledge spillovers from the stock of invented intermediate goods to the resource sector and the backstop sector. To be on the conservative side, technological progress is assumed to be resource using as long as energy generation relies exclusively on the resource.[3] Moreover, given that we are interested in the transition to the backstop era and not in this regime *per se*, we simplify the final regime by imposing technological progress to be Hicks neutral between intermediate goods and the backstop technology. The model is simple enough to analyze the dynamics and regime switches by using phase diagrams. To quantify the results, we calibrate the model and perform a numerical analysis that makes use of the relaxation algorithm put forward by Trimborn, Koch, and Steger (2008).

The remainder of the chapter is structured as follows. The main features of the model economy are presented in Section 2. Section 3 describes the solution procedure. Section 4 discusses the transitional dynamics and links the different regimes of energy generation. Section 5 provides the initial conditions needed to complete the solution of the model. Section 6 describes the calibration of the model and provides a simulation analysis. Finally, Section 7 concludes.

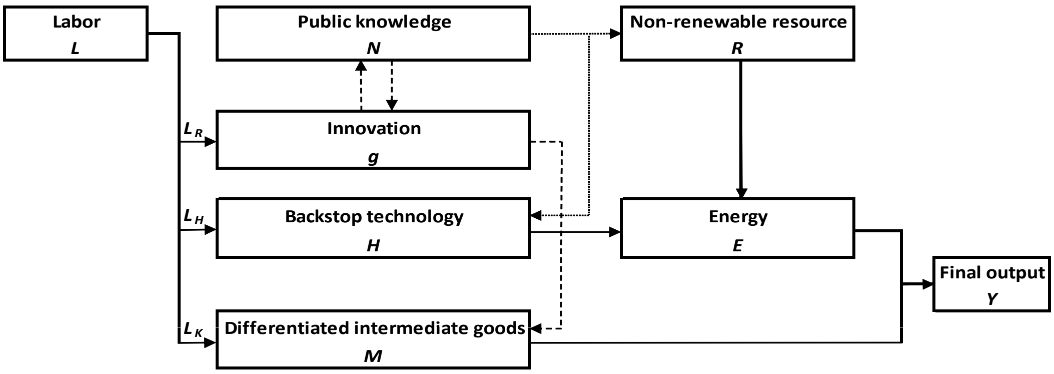
4.2 The Model

This section describes the structure of the model in detail. Figure 4.1 sets the stage by giving a schematic representation of the goods, factor, and knowledge

[3]The assumption of resource-using technical progress is in accordance with the analysis in Chapter 6, where a model with directed technical change is used to show that the economy converges to a regime in which $\delta = 0$.

flows in the model.

Figure 4.1: Schematic representation of goods, factor, and knowledge flows



4.2.1 Production

Final output Y is produced with energy E and an intermediate input M, according to

$$Y = \left[\bar{\theta} E^{\frac{\sigma-1}{\sigma}} + (1-\bar{\theta}) M^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \qquad (4.1)$$

where $0 < \bar{\theta} < 1$ is a parameter that regulates the relative productivity of the inputs and $\sigma > 0$ denotes the elasticity of substitution between energy and the intermediate input.[4]

The intermediate input is modeled as a CES aggregate of intermediate goods k with an elasticity of substitution between varieties of $1/(1-\beta) > 1$. At time t, there exists a mass of $N(t)$ different intermediate goods. When intermediate goods producers are identical, the equilibrium quantity of variety j is the same for all varieties, so that $k_j = k, \forall j$. By defining aggregate intermediate goods as $K \equiv Nk$, the intermediate input can be written as

$$M = \left(\int_0^N k_j^{\beta} dj\right)^{\frac{1}{\beta}} = N^{\phi} K,$$

where $\phi \equiv (1-\beta)/\beta$ measures the gains from specialization: while keeping aggregate intermediate goods K constant, the intermediate input M rises with the

[4]Time arguments are omitted if there is no possibility of confusion.

number of varieties N through increased specialization possibilities in the use of intermediate goods (cf. Ethier, 1982; Romer, 1987, 1990).

Energy is generated by the non-renewable resource R and a backstop technology H:

$$E = N^{\delta} R + N^{\xi} H, \tag{4.2}$$

where δ and ξ measure knowledge spillovers from the intermediate goods sector to resource extraction and backstop production, respectively.

Final goods producers maximize profits in a perfectly competitive market. They take their output price p_Y, the prices of intermediate goods p_{K_j}, the resource price p_R and the price of the backstop technology p_H as given. Because R and H are perfect substitutes, final good producers will only use the energy source with the lowest relative effective (i.e., corrected for productivity) price and they are indifferent between the two if their effective prices are equal. Relative demand for intermediate goods and energy is therefore given by:[5]

$$\begin{array}{llll} K/R = & \left(\frac{p_R}{p_K}\right)^{\sigma} \left(\frac{1-\bar{\theta}}{\bar{\theta}}\right)^{\sigma} N^{(\delta-\phi)(1-\sigma)}, & H = 0 & \text{if} \quad p_H N^{-\xi} > p_R N^{-\delta} \\ K/H = & \left(\frac{p_H}{p_K}\right)^{\sigma} \left(\frac{1-\bar{\theta}}{\bar{\theta}}\right)^{\sigma} N^{(\xi-\phi)(1-\sigma)}, & R = 0 & \text{if} \quad p_H N^{-\xi} < p_R N^{-\delta} \\ K/E = & \left(\frac{p_E}{p_K}\right)^{\sigma} \left(\frac{1-\bar{\theta}}{\bar{\theta}}\right)^{\sigma} N^{-\phi(1-\sigma)}, & & \text{if} \quad p_H N^{-\xi} = p_R N^{-\delta} \end{array}, \tag{4.3}$$

where p_E denotes the price of energy. We define the income shares of energy and intermediate goods, and the expenditure shares of the backstop technology and the resource in total energy costs as follows:

$$\theta \equiv \frac{p_E E}{p_Y Y}, \qquad 1-\theta = \frac{p_K K}{p_Y Y}, \qquad \omega \equiv \frac{p_H H}{p_E E}, \qquad 1-\omega = \frac{p_R R}{p_E E}. \tag{4.4}$$

As long as energy generation relies exclusively on the resource (i.e., when $H = 0$), it follows from (4.3) that technological progress, being defined as an increase in N, is resource-using if $(\phi-\delta)(1-\sigma) > 0$ and resource-saving if $(\phi-\delta)(1-\sigma) < 0$. To be on the conservative side, we assume poor substitution between energy and the intermediate input, i.e. $0 < \sigma < 1$ and weak knowledge spillovers to the resource sector, i.e. $\nu \equiv \phi - \delta > 0$, where ν measures the bias of technological change. As a result, technological progress is resource-using in this regime. Below we will show that the economy converges to a regime in which energy generation relies exclusively on the backstop technology. Given that we are not interested in this

[5] Appendix 4.A.1 derives the relative factor demand by solving the profit maximization problem of final good producers.

regime *per se* but merely in the preceding equilibrium path, we simplify the final phase by assuming Hicks neutral technological progress, i.e. we impose $\xi = \phi$.[6]

Firms in the intermediate goods sector have to buy a patent that allows each of them to produce one specific variety according to:

$$k_j = l_{K_j} \Rightarrow K = L_K, \tag{4.5}$$

where l_{K_j} denotes labor demand by firm j and L_K is aggregate labor demand by the intermediate goods sector. Imperfect substitutability between varieties implies that the intermediate goods market is characterized by monopolistic competition. Each producer maximizes profits and faces a demand elasticity of $(1+\phi)/\phi$. As a result, all firms charge the same price of a mark-up $1+\phi$ times marginal cost, which equals the wage rate w:

$$p_K = (1+\phi)w. \tag{4.6}$$

Profits of intermediate goods producers are used to cover the costs of obtaining a patent. Combining (4.5) and (4.6), profits for each firm are given by:

$$\pi = p_K k - wk = \frac{\phi w K}{N}. \tag{4.7}$$

Firms in the perfectly competitive backstop technology sector use labor to produce the backstop according to:

$$H = \eta L_H, \tag{4.8}$$

where L_H denotes aggregate labor demand by the backstop technology sector. The price of one unit of the backstop equals its marginal cost:

$$p_H = \frac{w}{\eta}. \tag{4.9}$$

4.2.2 Research and Development

Research and development (R&D) undertaken by firms in the research sector leads to the invention of new intermediate good varieties. Following Romer (1990), we assume that the stock of public knowledge evolves in accordance with the number of invented intermediate goods. New varieties are created according to the following innovation possibilities frontier (IPF):

$$\dot{N} = \frac{1}{a} L_R N, \tag{4.10}$$

[6]The assumption $\xi = \phi$ is equivalent to assuming that the backstop technology uses final output instead of labor and $\xi = 0$.

where L_R denotes labor allocated to research and a is a productivity parameter. The right hand side of the IPF features the stock of public knowledge, to capture the 'standing on shoulders effect': researchers are more productive if the available stock of public knowledge is larger (cf. Romer, 1990). We define the innovation rate as

$$g \equiv \frac{\dot{N}}{N}. \tag{4.11}$$

Free entry of firms in the research sector implies that whenever the cost of inventing a new variety, wa/N, is lower than the market price of a patent, p_N, entry of firms in the research sector will take place until the difference is competed away. Therefore, free entry gives rise to the following condition:

$$aw/N \geqslant p_N \qquad \text{with equality (inequality) if } g > 0 \ (g = 0). \tag{4.12}$$

The market value of a patent equals the present discounted stream of profits that it generates:

$$p_N(t) = \int_t^\infty \pi(z) e^{\int_t^z r(s)ds} dz,$$

where r denotes the nominal interest rate. Differentiating this expression with respect to time, we find

$$\pi + \dot{p_N} = r p_N, \tag{4.13}$$

which can be interpreted as a no-arbitrage condition that requires investors to earn the market interest rate on their investment in patents. By combining (4.6), (4.7), (4.11), (4.12), and (4.13), we obtain an expression for the return to innovation deflated with the intermediate goods price:

$$r - \hat{w} = r - \hat{p}_K = \frac{\phi}{a} K - g \text{ if } g > 0, \tag{4.14}$$

where hats denote growth rates. The return to innovation depends positively on K, because of a market size effect, and negatively on g, because fast innovation implies a rapidly decreasing patent price. The parameters a has a negative effect on the return to innovation, because it is related negatively to the productivity of researchers. The parameter ϕ has a positive effect, because of its positive relationship with the mark-up on the price of intermediate goods.

4.2.3 Factor Markets

Equilibrium on the labor market requires that aggregate labor demand from the intermediate goods sector, the backstop technology sector, and the research sector equals the fixed labor supply L:

$$L_K + L_H + L_R = K + \frac{H}{\eta} + ag = L. \tag{4.15}$$

Using (4.4), (4.6), (4.8), and (4.15), labor market equilibrium implies:

$$K = \frac{(1-\theta)}{(1+\phi)\omega\theta + (1-\theta)} (L - ag). \tag{4.16}$$

Resource extraction depletes the resource stock S according to:

$$\dot{S}(t) = -R(t), \quad S(0) = S_0, \quad R(t) \geqslant 0, \quad S(t) \geqslant 0, \tag{4.17}$$

which implies that total extraction cannot exceed the initial resource stock.

4.2.4 Households

The representative household lives forever, derives utility from consumption of the final good, and inelastically supplies L units of labor at each moment. It owns the resource stock with value $p_R S$ and all equity in intermediate goods firms with value $p_N N$. The household maximizes lifetime utility[7]

$$U(t) = \int_t^\infty \ln Y(z) e^{-\rho(z-t)} dz,$$

subject to its flow budget constraint[8]

$$\dot{V} = r(V - p_R S) + \dot{p}_R S + wL - p_Y Y, \tag{4.18}$$

and a transversality condition:

$$\lim_{z\to\infty} \lambda(z) V(z) e^{-\rho z} = 0, \tag{4.19}$$

where ρ denotes the pure rate of time preference, V total wealth, and λ the shadow price of wealth.

[7] Note that final output cannot be stored, so that consumption equals output.

[8] Appendix 4.A.2.1 shows the derivation of the flow budget constraint of the households.

Straightforward manipulations of the standard first-order conditions for the optimization problem of the representative household, which can be found in Appendix 4.A.2.2, yield two familiar rules:

$$\hat{p}_Y + \hat{Y} = r - \rho, \tag{4.20}$$

$$\hat{p}_R = r. \tag{4.21}$$

The first one, (4.20), is the Ramsey rule, which relates the growth rate of consumer expenditures to the difference between the nominal interest rate and the pure rate of time preference. Equation (4.21) is the Hotelling rule, which ensures that owners of the resource stock are indifferent between (i) selling an additional unit of the resource and investing the revenue at the interest rate r, and (ii) conserving it and earn a capital gain at rate $\hat{p}_R$.

4.3 Solving the Model

In this section, we provide the solution to the model. We will show that the economy experiences at most three consecutive regimes of energy generation: (i) only the resource is used (RUO), (ii) simultaneous use of the resource and the backstop technology (SU), and (iii) only the backstop technology is used (BTO). It depends on the parameter configuration and the initial resource and knowledge stocks which regimes actually exist. We start the solution procedure by first describing the dynamic behavior of the economy during each regime. Subsequently, we use the matching conditions to link the regimes together.

4.3.1 Regime 1: Resource Use Only

During the RUO regime, energy generation relies exclusively on the natural resource.[9] The model described in Section 4.2 constitutes a dynamic system with two predetermined (state) variables: N and S. The analysis and the visualization of the dynamics of such a system is complex. However, we are able to condense the model to a three-dimensional block-recursive system of differential equations in the energy income share θ, the innovation rate g, and the reserve-to-extraction rate $y \equiv S/R$. The system is block-recursive in the sense that the system of θ and g can be solved independently from y. All growth rates in the model can be expressed in

[9] The RUO regime exists if the initial stock is large enough, as discussed in Section 4.4

terms of θ and g. Subseqently, the differential equation for y can be used to solve for the initial reserve-to-extraction rate, which pins down the initial levels of all variables in the model. In this section, we analyze the (θ, g)-subsystem described in Proposition 4.1, and we postpone the solution of the differential equation for y until Section 4.5.

Proposition 4.1. *Provided that $g(t) > 0$, the dynamics in the RUO regime are described by the following two-dimensional system of first-order nonlinear autonomous differential equations in $\theta(t)$ and $g(t)$:*

$$\dot{\theta}(t) = \theta(t)[1 - \theta(t)](1 - \sigma)\left[r(t) - \hat{w}(t) + \nu g(t)\right], \tag{4.22}$$

$$\dot{g}(t) = \left[\frac{L}{a} - g(t)\right]\{\rho + \theta(t)(1 - \sigma)\nu g(t) - [1 - \theta(t)(1 - \sigma)]\left[r(t) - \hat{w}(t)\right]\}, \tag{4.23}$$

where, at an interior solution, the term $r(t) - \hat{w}(t)$ is a function of $g(t)$:

$$r(t) - \hat{w}(t) = \phi\frac{L}{a} - (1 + \phi)g(t). \tag{4.24}$$

Proof. See Appendix 4.A.3. □

Beyond simplifying the mathematical analysis, the re-expression of the model in terms of θ and g also helps to clarify the economics behind our results. These state variables, namely, have a clear interpretation as they are indicators of energy scarcity and the rate of technical progress, respectively. By imposing $\dot{\theta} = \dot{g} = 0$, (4.22)-(4.24) give rise to the following steady state loci:[10]

$$g|_{\dot{\theta}=0} = \frac{L}{a}\frac{\phi}{1 + \delta}, \tag{4.25}$$

$$g|_{\dot{g}=0} = \frac{\rho + \phi(L/a)\left[(\theta(1 - \sigma) - 1\right]}{\theta(1 - \sigma)(1 + \delta) - (1 + \phi)}. \tag{4.26}$$

Resource extraction growth in the RUO regime is obtained by converting the first line of the relative factor demand function (4.3) into growth rates, and combining the obtained expression with (4.4), (4.20), (4.21):

$$\hat{R} = (1 - \theta)(1 - \sigma)(r - \hat{w} + \nu g) - \rho. \tag{4.27}$$

[10] Appendix 4.A.4 shows the first-order derivatives of the steady state loci with respect to θ.

Solving (4.27) for g and imposing $\hat{R}=0$ and (4.24), we find an expression for the $\hat{R}=0$-isocline:

$$g|_{\hat{R}=0} = g|_{\dot{\theta}=0} - \frac{\rho}{(1-\sigma)(1+\delta)(1-\theta)}. \tag{4.28}$$

To facilitate our discussion of the dynamics in this regime, we finally need an expression for the real interest rate, i.e. the nominal rate of interest deflated with the price index of final goods:

$$r - \hat{p}_Y = (1-\theta)(r - \hat{w} + \nu g) + \delta g = (1-\theta)\left[\frac{\phi}{a}L - (1+\delta)g\right] + \delta g, \tag{4.29}$$

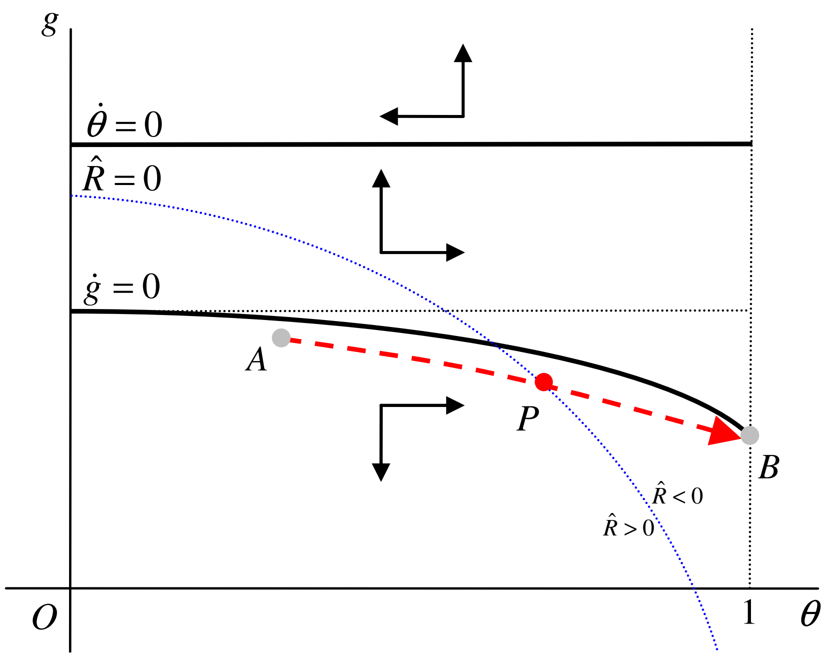
if $g > 0$, where the first and second equality use $\hat{p}_Y = \theta(r - \delta g) + (1-\theta)(\hat{w} - \phi g)$ and (4.24), respectively.

We further examine the dynamics of the RUO regime in the phase diagram in (θ, g)-space as shown in Figure 4.2. The income share locus $\dot{\theta} = 0$ represents (4.25) and gives combinations of θ and g for which the energy income share is constant. There is a unique innovation rate that leads to a constant energy income share, so that the income share locus is horizontal at this specific value of g. Intuitively, the growth rates of the effective prices of intermediate goods and energy are equal along the $\dot{\theta} = 0$ line, leading to constant income shares. At points below the income share locus, the effective price of energy relative to the intermediate goods increases ($r - \hat{w} + \nu g > 0$), so that the income share of energy rises over time and *vice versa*. The dynamic behavior of θ is illustrated by the horizontal arrows in the phase diagram.[11]

The innovation locus $\dot{g} = 0$ represents (4.26) and gives combinations of θ and g for which the innovation rate is constant over time. The $\dot{g} = 0$ line is downward sloping, because an increase in θ leads to a lower real interest rate (see (4.29)) and therefore to slower output growth. As a result, K tends to decrease over time, which induces a flow of labor from the production to the research sector, causing the innovation rate to rise over time. To counteract this effect, g must decrease thereby enhancing the growth rate of labor demand as a result of its combined effect on output growth (through the real interest rate) and the productivity of the factors of production. At points to the right of the innovation locus, the real interest rate and output growth are lower than in steady state equilibrium, so that K declines and the innovation rate increases over time and *vice versa*. The dynamic behavior of g is illustrated by the vertical arrows in the phase diagram.

[11] Appendix 4.A.4 derives the direction of the arrows.

Figure 4.2: Phase diagram in (θ, g) space: RUO regime



Notes: The dashed arrow represents the unique equilibrium path that leads to point B, governed by the dynamic system for θ and g. The solid lines represent the isoclines for θ and g. The dotted line gives the extraction isocline (case $\Delta_2 > 0$).

The extraction isocline $\hat{R} = 0$ represents (4.28) and gives combinations of θ and g for which extraction growth equals zero. The $\hat{R} = 0$ line is downward sloping, because a decrease in θ boosts the real interest rate and therefore the growth rates of output and resource demand. To counteract this effect, g must increase to slow down the growth of resource demand through its combined effect on the real interest rate and the efficiency of resource extraction. At points to the right of the $\hat{R} = 0$ isocline, the real interest rate and therefore output growth are lower than required for constant extraction, so that extraction growth becomes negative and *vice versa*.

Because it will affect the dynamics of the model, it is important to determine the relative positions of the three lines in the phase diagram. First, given that $\nu > 0$, the innovation locus (4.26) cannot intersect the income share locus (4.25) and the former is always located below the latter in (θ, g)-space. Second, it is clear from (4.28) that the extraction isocline cannot intersect the income share locus either. Furthermore two important boundary properties of the extraction isocline are given by:

$$\lim_{\theta \to 1} g|_{\hat{R}=0} = -\infty, \qquad (g|_{\hat{R}=0})\,|_{\theta=0} = g|_{\dot{\theta}=0} - \frac{\rho}{(1-\sigma)(1+\delta)}.$$

Without the existence of a backstop technology, the RUO regime lasts forever and the economy converges along the stable manifold from point A to point B in Figure 4.2.[12] This equilibrium path is characterized by an ever decreasing innovation rate and an income share of energy that converges to unity. The occurrence of peak-oil in the model without a backstop technology depends on the following differences: $\Delta_1 \equiv g|_{\hat{R}=0,\theta=0} - g|_{\dot{g}=0,\theta=1}$ and $\Delta_2 \equiv g|_{\hat{R}=0,\theta=0} - g|_{\dot{g}=0,\theta=0}$. The signs of the Δ's depend crucially on the elasticity of substitution between intermediate goods and energy: $\lim_{\sigma \to 1} \Delta_1 = -\infty$ and $\Delta_2|_{\sigma=0} > 0$.[13] Hence, the extraction isocline will intersect the innovation locus if σ is small and will be located below it if σ is high. The time path of resource extraction will either be hump-shaped, or decreasing from the beginning, as described in Claim 4.1.

Claim 4.1. *In the model without a backstop technology, peak-oil can only occur if* $\Delta_2 > 0$. *If* $\Delta_1 < 0$, *the time path of resource extraction is downward sloping from the beginning.*

Proof. If $\Delta_1 < 0$, the extraction isocline is located entirely below the innovation locus in the (θ, g)-plane, and if $\Delta_2 > 0$, both lines intersect exactly once. Along the saddle path, $g \in (g|_{\dot{g}=0,\theta=1}, g|_{\dot{g}=0,\theta=0})$. Hence, if $\Delta_1 < 0$ the extraction isocline is located entirely below the saddle path of the dynamic system. If $\Delta_2 > 0$ the saddle path crosses the extraction isocline once if the initial income share is low enough. Resource extraction then increases temporarily, and peaks when the economy crosses point P in Figure 4.2. □

When the existence of a backstop technology is taken into account, the economy does not converge to point B and will eventually shift to another dynamic regime. The end point (g, θ) in the phase diagram of the RUO regime now depends on the relative price of the backstop technology and intermediate goods and on economic conditions in the subsequent regimes, which will be described below.

[12] Appendix 4.A.5 shows that point B in figure 4.2 is the only attainable steady state of the model without a backstop technology that satisfies the transversality condition (4.19).

[13] The expressions for the Δ's are shown in Appendix 4.A.6.

4.3.2 Regime 2: Simultaneous Use

The solution to the simultaneous use (SU) regime is characterized by a constant income share of energy and a closed-form differential equation for the innovation rate, which are both given in Proposition 4.2.

Proposition 4.2. *In the SU regime, the income share of energy θ remains constant at its right after switching' (RAS) value and equal to*[14]

$$\theta_2^+ = \left[[\eta(1+\phi)]^{1-\sigma} \left(\frac{1-\bar{\theta}}{\bar{\theta}} \right)^{\sigma} + 1 \right]^{-1} \tag{4.30}$$

The innovation rate is decreasing over time, according to the following differential equation

$$\dot{g} = -g(\nu g + \rho). \tag{4.31}$$

Proof. See Appendix 4.A.7. □

Intuitively, as long as $\theta < \theta_2^+$, the resource is relatively cheaper than the backstop technology so that only the resource will be used for energy generation. If $\theta = \theta_2^+$, effective prices of the resource and the backstop technology are equal, which enables a regime of simultaneous use as long as θ remains constant. The declining innovation rate follows from the constant energy and intermediate goods income share during the simultaneous use regime. A constant income share requires that the relative price of intermediate goods and energy remains unchanged: $r - \hat{w} + \nu g = 0 \Rightarrow r - \hat{w} = -\nu g < 0$. As a result, K goes down over time, because the constant income share implies $\hat{K} + \hat{w} = r - \rho \Leftrightarrow \hat{K} = r - \hat{w} - \rho$. According to (4.14), g consequently needs to decline in order to ensure that $r - \hat{w} = -\nu g < 0$ remains satisfied.

Combining (4.30) with the production function (4.1), final output in the SU regime can be written as:

$$Y = N^{\phi} \left(\frac{1-\bar{\theta}}{1-\theta_3^+} \right)^{\frac{\sigma}{\sigma-1}} K. \tag{4.32}$$

Differentiating (4.32) and using (4.31) gives the growth rate of final output in the SU regime:

$$\hat{Y} = \delta g - \rho,$$

[14] We use the conventional shortcut notation $x_j^+ \equiv \lim_{t \downarrow T_{ij}} x_j(t)$ and $x_{ij}^- \equiv \lim_{t \uparrow T_{ij}} x_i(t)$.

where the evolution of the innovation rate is described by the differential equation in Proposition 4.2. Its starting and end point will be determined below by using the matching conditions that link the different regimes together.

4.3.3 Regime 3: Backstop Technology Only

Because of our assumption of Hicks neutral technological progress in this regime, the production function reduces to:

$$Y = N^{\phi}\left[\bar{\theta}H^{\frac{\sigma-1}{\sigma}} + (1-\bar{\theta})K^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}. \tag{4.33}$$

The solution to the 'backstop technology only' (BTO) regime is characterized by the expressions for the income share of energy and the innovation rate given in Proposition 4.3.

Proposition 4.3. *In the BTO regime, the income share of energy θ and the innovation rate g remain constant at their RAS values, which are given by*

$$\theta_3^+ = \theta_2^+, \tag{4.34}$$

$$g_3^+ = \left(\frac{L}{a} + \rho\right)\frac{\phi}{1+\phi}(1-\theta_3^+) - \rho. \tag{4.35}$$

Proof. See Appendix 4.A.8. □

Intuitively, Hicks neutral technical change implies a fixed income shares of energy and intermediate goods. Given that the resource stock is depleted, innovation is the only remaining investment possibility. The constant income share of intermediate goods implies an unchanging return to innovation, resulting in a constant innovation rate over time. Substitution of (4.3), (4.30), and (4.34) into (4.33), gives an expression for final output in the BTO regime:

$$Y = N^{\phi}\left(\frac{1-\bar{\theta}}{1-\theta_3^+}\right)^{\frac{\sigma}{\sigma-1}} K_3^+. \tag{4.36}$$

Differentiating the labor market equilibrium (4.16) and using the constancy of g and θ, it follows that K is constant too in the BTO regime, so that final output growth is given by:

$$\hat{Y} = \hat{Y}_3^+ = \phi g_3^+.$$

4.3.4 Linking the Regimes

We will use Ramsey rule (4.20) to link the different regimes: as long as the real interest rate is finite, consumption should be continuous at the regime shifts:

$$Y_{ij}^{-} = Y_{j}^{+}. \tag{4.37}$$

4.4 Transitional Dynamics and Regime Shifts

In this section, we construct phase diagrams to describe the transitional dynamics of the model and to characterize the different regime shifts that the economy may experience. We have to examine several scenarios and use backward induction, because the equilibrium path that the economy follows during the a certain regime depends on the characteristics of the subsequent regime.

We assume that the initial resource stock is large enough to ensure that the natural resource is relatively cheap compared to its perfect substitute so that the backstop technology is not competitive yet. Formally, this is the case in the RUO regime when $p_H N^{-\xi} > p_R N^{-\delta}$, which implies

$$\theta(t) < \theta_2^{+} = \theta_3^{+} \equiv \theta^{+}. \tag{4.38}$$

Over time, according to (4.22), θ is increasing until inequality (4.38) is no longer satisfied. At this moment, the economy will move from the RUO regime to another regime of energy generation in which the dynamics are no longer described by the system of differential equations in Proposition 4.1. Depending on the parameter configuration, there are two possibilities at the end of the RUO regime: (i) the economy shifts to the SU regime, and (ii) the economy shifts to the BTO regime. Because the equilibrium path that the economy follows during the RUO regime depends on the characteristics of the subsequent regime, we will discuss both scenarios in turn.

4.4.1 From Resource Use Only to Backstop Technology Only

In this scenario, the economy shifts from regime 1 to regime 3 at time T_{13}, when the following equality holds:

$$p_H(T_{13}^{-})N(T_{13}^{-})^{-\xi} = p_R(T_{13}^{-})N(T_{13}^{-})^{-\delta}. \tag{4.39}$$

By using (4.39) and $\xi = \phi$ in the first line of the relative demand function (4.3), we find $\theta_{13}^{-} = \theta^{+}$, which implies that θ is continuous at the regime shift. Substitution of θ^{+} into (4.1) gives an expression for output at the very end of the RUO regime:

$$Y_{13}^{-} = (N_{13}^{-})^{\phi} \left(\frac{1-\bar{\theta}}{1-\theta^{+}} \right)^{\frac{\sigma}{\sigma-1}} K_{13}^{-}. \tag{4.40}$$

Combining (4.40) and (4.36) and using the continuity of θ and N, the matching condition (4.37) requires $K_{13}^{-} = K_{3}^{+}$. Labor market equilibrium (4.16) with $\omega_{13}^{-} = 0$ and $\omega_{3}^{+} = 1$, allows us to rewrite the matching condition as:

$$L - ag_{13}^{-} = \left(\frac{(1-\theta^{+})}{\theta^{+}(1+\phi) + 1 - \theta^{+}} \right) \left(L - ag_{3}^{+} \right). \tag{4.41}$$

Substitution of (4.35) for g_{3}^{+} and solving (4.41) for g_{13}^{-}, we find:

$$g_{13}^{-} = \frac{L}{a} - \frac{1-\theta^{+}}{1+\phi} \left(\frac{L}{a} + \rho \right). \tag{4.42}$$

Hence, the innovation rate jumps down at the regime shift to free enough labor for the production of energy with the backstop technology while keeping $K = L_K$ unaffected.

Proposition 4.4. *The innovation rate at the switching time T_{13} jumps down from g_{13}^{-} to g_{3}^{+}.*

Proof. Subtracting (4.35) from (4.42), we find

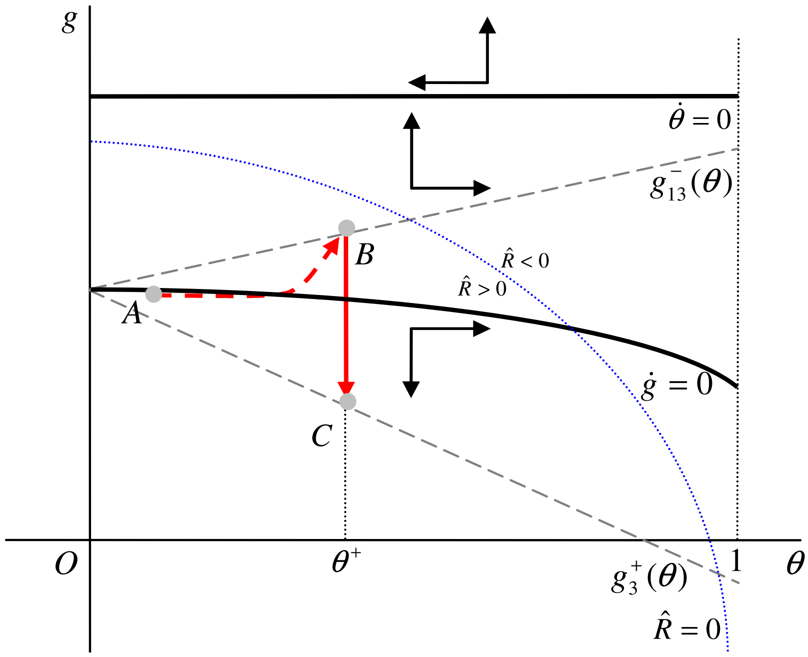
$$g_{13}^{-} - g_{3}^{+} = \theta^{+} \left(\frac{L}{a} + \rho \right) > 0. \quad \square$$

Figure 4.3 shows the end point (θ^{+}, g_{13}^{-}), labeled B, to which the economy converges in the RUO regime. The equilibrium path that leads to this end point is indicated by the dashed arrow. Along this path, the innovation rate is higher than it would have been in an economy without the backstop technology available (see Figure 4.2). The figure also contains the extraction isocline and lines for g_{3}^{+} and g_{13}^{-} as functions of θ. Note that the end point (θ^{+}, g_{13}^{-}) is located below the $\dot{\theta} = 0$ line, which is a necessary condition for the regime switch from RUO to BTO to occur.

Proposition 4.5. *If the economy shifts from the RUO regime to the BTO regime, the following inequality should hold:*

$$g_{13}^{-} \leqslant \frac{\phi}{1+\delta} \frac{L}{a}. \tag{4.43}$$

Figure 4.3: Phase diagram in (θ, g) space: from RUO to BTO



Notes: The dashed arrow represents the unique equilibrium path that leads to point B, governed by the dynamic system for θ and g. The solid lines represent the isoclines for θ and g. The dotted line gives the extraction isocline. The dashed gray lines represent g_{13}^{-} and g_3^{+} as functions of θ.

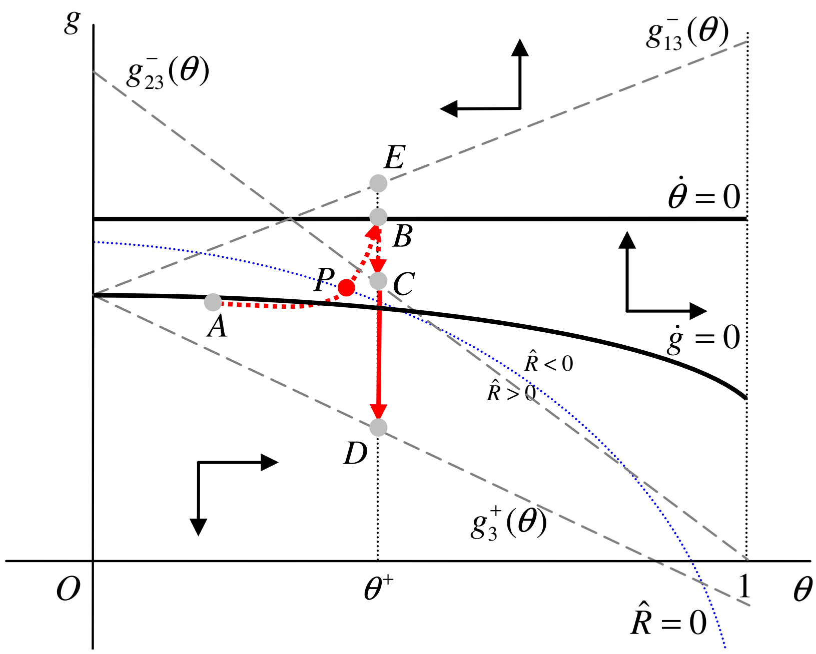
Proof. By contradiction: If (4.43) does not hold, the dynamic path in the RUO regime that leads to (θ^{+}, g_{13}^{-}) necessarily intersects the vertical θ^{+} line before the RUO regime has ended. This would imply that only the resource is being used while the backstop technology is relatively cheaper, which violates optimality of the behavior of final good producers. □

Along the equilibrium path in Figure 4.3, the income share of energy is increasing over time. The innovation rate is initially decreasing, but as soon as the economy crosses the innovation locus, the growth rate starts to increase until the moment of the regime switch. Intuitively, in order to prevent consumption from falling discontinuously when the resource stock is exhausted, the representative household now starts to increase savings when the regime switch comes near. In so doing, the household effectively smooths consumption by converting part of the resource wealth into knowledge, thereby transferring consumption possibilities to the future regime in which the resource stock is depleted. In the figure, resource extraction peaks when the saddle path crosses the extraction isocline at point P and decreases afterwards. However, the extraction path might also be upward sloping during the whole time span of the RUO regime, if it would be located entirely above the equilibrium path.

4.4.2 From Resource Use Only to Simultaneous Use

If condition (4.43) is not satisfied, the economy will not experience a sudden shift from a regime in which energy is generated by the natural resource only to an era in which energy generation relies exclusively on the backstop technology. In this case, the shift from the natural resource to the backstop technology occurs more gradually, trough a regime in which both energy sources are used simultaneously.

Figure 4.4: Phase diagram in (θ, g) space: from RUO to SU



Notes: The curved dotted arrow represents the unique equilibrium path of the RUO regime that leads to point B, governed by the dynamic system for θ and g. The straight dotted arrow shows the equilibrium path of the SU regime, leading to point C. The solid arrow represents the jump from point B to C at the end of the SU regime. The solid lines represent the isoclines for θ and g. The dotted line gives the extraction isocline. The dashed gray lines represent g_{13}^{-}, g_{23}^{-}, and g_3^{+} as functions of θ.

Substitution of θ^{+} into (4.1) gives an expression for output at the very end of the RUO regime:

$$Y_{12}^{-} = (N_{12}^{-})^{\phi} \left(\frac{1 - \bar{\theta}}{1 - \theta^{+}} \right)^{\frac{\sigma}{\sigma - 1}} K_{12}^{-}. \tag{4.44}$$

Combining (4.32) and (4.44) and using the continuity of θ and N, the matching condition (4.37) requires $K_{12}^{-} = K_2^{+}$. Together with the labor market equilibrium (4.16) with $\omega_{12}^{-} = 0$, this equality implies:

$$L - ag_{12}^{-} = \frac{1-\theta^{+}}{\omega_2^{+}\theta^{+}(1+\phi)+1-\theta^{+}}\left(L - ag_2^{+}\right). \tag{4.45}$$

We derive a relationship between ω and g in the SU regime by substituting the labor market equilibrium (4.16) into the innovation return equation (4.14) noting that $r - \hat{w} = -\nu g$:

$$\omega = \frac{\phi L - ag(1+\delta)}{ag(1+\phi)(1-\phi+\delta)}\frac{1-\theta}{\theta}. \tag{4.46}$$

Using this relationship to substitute for ω_2^{+} in (4.45), the matching condition reduces to

$$L - ag_{12}^{-} = \frac{a}{\phi}(1-\nu)g_2^{+}. \tag{4.47}$$

This matching condition implies that the innovation rate is continuous at time T_{12}, when the economy shifts from regime 1 to regime 2.

Proposition 4.6. *The innovation rate at the switching time T_{12} is continuous and equal to:*

$$g_{12}^{-} = g_2^{+} = \frac{\phi}{1+\delta}\frac{L}{a}. \tag{4.48}$$

Proof. The innovation rate g_{12}^{-} cannot exceed $\phi/(1+\delta)(L/a)$, because otherwise the dynamic path in the RUO regime necessarily intersects the vertical θ^{+} line before the RUO regime has ended. This would imply that only the resource is being used while the backstop technology is relatively cheaper, which violates optimality of the behavior of final good producers. Given that $\omega \geqslant 0$, it follows from (4.46) that the innovation rate g_2^{+} also cannot exceed $(L/a)\phi/(1+\delta)$. Consequently, the only solution to (4.47) is given by equation (4.48) in Proposition 4.6. □

Figure 4.4 shows the end point $(\theta_{12}^{-}, g_{12}^{-})$, indicated by B, and the equilibrium path towards it in the RUO regime before the switch to simultaneous use takes place. Hence, the economy moves from point A to point B in the figure. Point E cannot be reached, because of the argument provided in the proof of Proposition 4.6. The income share of energy increases over time, while the innovation rate again exhibits a non-monotonic time profile: it decreases initially but starts to increase once the economy has passed the innovation locus. The saddle path necessarily crosses the extraction isocline, so that resource extraction peaks at point P and decreases afterwards.

The existence of a simultaneous use regime depends on the profitability of innovation (i.e., on ϕ) and on the costs of the backstop technology, (i.e., on η). If innovation revenues would be zero (i.e, if $\phi = 0$), there would be no investment in R&D at all. Without investment in R&D, there necessarily exists a regime of simultaneous use. The reason is that in this scenario resource use has to decline gradually to zero, in order to prevent a jump in marginal utility. Near the regime shift, the marginal product of energy would be very high if all labor would remain in the production sector. Therefore, in the equilibrium labor starts to flow from the intermediate goods sector to the backstop sector before the shift to the backstop era.[15] Simultaneous use is the only way to smooth consumption by shifting part of the resource wealth to the future. Accordingly, savings behavior of the households ensures that the interest rate is equal to the growth rate of the backstop price. In a market equilibrium with positive R&D (when $\phi > 0$), households have an additional way to smooth consumption: by reducing innovation at the time of the regime shift, labor becomes available for energy generation with the backstop technology without a need to reduce consumption. In scenarios with profitable innovation possibilities and a relatively cheap backstop technology, consumption smoothing may completely take place through this new channel: simultaneous use will not occur. If, however, innovation is less profitable, or the backstop technology is relatively expensive so that it will absorb a substantial amount of the labor supply after the regime switch, part of the consumption smoothing still takes place through a temporary regime of simultaneous use, during which the production of the backstop technology starts from zero at the beginning of this regime and gradually increases to its mature long-run level.

4.4.3 From Simultaneous Use to Backstop Technology Only

Combining (4.32) and (4.36), and using the continuity of θ and N, the matching condition (4.37) requires $K_{23}^{-} = K_3^{+}$. Together with the labor market equilibrium

[15]Another explanation is that if $g = 0$, $L = L_K + L_H$, so that any jump in L_H will imply a jump in L_K and hence in consumption and marginal utility. Therefore, L_H must gradually increase from zero to its long-run value.

(4.16) with $\omega_3^+ = 1$, this equality implies:

$$\frac{1-\theta^+}{\omega_{23}^-\theta^+(1+\phi)+1-\theta^+}\left(L-ag_{23}^-\right)=\frac{1-\theta^+}{\theta^+(1+\phi)+1-\theta^+}\left(L-ag_3^+\right).$$

Substitution of (4.46) for ω_{23}^- on the left hand side and (4.35) for g_3^+ on the right hand side, gives an expression for the innovation rate at the end of the SU regime:

$$g_{23}^- = \frac{\phi(1-\theta)(L+a\rho)}{a(1+\phi)(1-\nu)} > 0, \tag{4.49}$$

where the inequality follows from $\nu < 1$, which is required for the SU regime to exist.[16]

Proposition 4.7. *The innovation rate at the switching time T_{23} jumps down from g_{23}^- to g_3^+.*

Proof. Subtracting (4.35) from (4.49), we find:

$$g_{23}^- - g_3^+ = \frac{L\nu\phi(1-\theta)+a\left[(1-\nu)(1+\phi)+\nu\phi(1-\theta)\right]\rho}{a(1-\nu)} > 0. \quad \square$$

The evolution of the innovation rate from g_2^+ to g_{23}^- during the SU regime and the jump from g_{23}^- to g_3^+ at T_{23} are indicated by the dashed arrow from point B to point C and the solid arrow from point C to point D in Figure 4.4, respectively. The figure also contains a line for g_{23}^- as a function of θ.
By using the expenditure share definition (4.4), the Hotelling rule (4.21), the backstop price (4.9), and $\hat{E} = \hat{K} = -\nu g - \rho$, we find the growth rate of resource extraction:

$$\hat{R} = -\frac{\omega}{1-\omega}\hat{\omega} - \rho = -\frac{\nu\phi(1-\theta)L + a\left[(1-\nu)(1+\phi)+\nu\phi(1-\theta)\right]\rho}{a\theta(1-\nu)(1-\omega)(1+\phi)} < 0,$$

where the last equality uses (4.46) and the labor market equilibrium (4.16). Hence, resource extraction decreases over time during the SU regime.

4.5 Initial Conditions

To determine the initial value for the energy income share θ, we exploit the fact that total resource extraction over time should be equal to the initial resource

[16] The SU regime can only exist if the g_{13}^- line in Figure (4.4) intersects the income share locus, which requires $\nu < 1$.

stock. We derive a differential equation for the reserve-to-extraction rate $y \equiv S/R$ in terms of y, θ and g. Together with the already determined saddle path in (θ, g)-space, the differential equation for the reserve-to-extraction rate gives rise to a unique equilibrium path in (θ, y)-space that leads to a zero reserve-to-extraction rate at the moment of the switch to the BTO regime (i.e. at $t = T_{i3}$). Then, we use the relative factor demand function and the function $g = f(\theta)$, which is defined by the saddle path in (θ, g)-space, to derive a relationship between the initial θ and y. The initial income share θ then follows from the intersection of the equilibrium path and the initial relative factor demand function in (g, y)-space. We study the scenarios with and without simultaneous use in turn.

4.5.1 No Simultaneous Use

If the economy shifts from the RUO to the BTO regime without an intervening period of simultaneous use, the reserve-to-extraction rate should equal zero at the end of the RUO regime. The first row in the relative factor demand function (4.3) can be written as:

$$\frac{\theta}{1-\theta} = \frac{\bar{\theta}}{1-\bar{\theta}} \left(\frac{yKN^{\nu}}{S} \right)^{\frac{1-\sigma}{\sigma}}. \tag{4.50}$$

Converting (4.50) into growth rates, we obtain

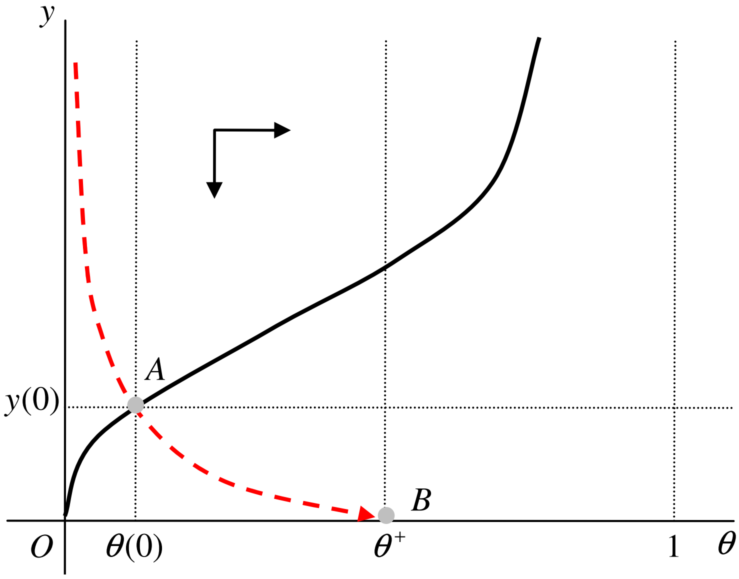
$$\hat{\theta} = (1-\theta)\frac{1-\sigma}{\sigma} \left(\hat{K} + \nu g + \hat{y} - \hat{S} \right).$$

By using (A.4.11), (A.4.13) and $\hat{S} = -y^{-1}$, we get the differential equation for y in terms of y, θ, and g:

$$\dot{y} = -y(1-\theta)(1-\sigma) \left[\phi \frac{L}{a} - (1+\delta)g \right] + y\rho - 1. \tag{4.51}$$

Imposing the end point $y(T_{13}^{-}) = 0$ and using the already determined time paths of θ and g, the differential equation (4.51) yields a unique equilibrium path for y in (θ, y)-space. By plugging the initial stocks N_0 and S_0 into (4.50) and using the labor market equilibrium (4.16) to substitute for K, we obtain a second relationship between θ and y. A combination of the two relationships yields the starting point $[\theta(0), y(0)]$ that is consistent with complete depletion of the resource stock. The starting point corresponds with point A in Figure 4.5, where the dashed arrow represents the unique equilibrium path that leads to point B, governed by the dynamic system for θ, g and y, and the solid line gives the relationship between $\theta(0)$

Figure 4.5: Determining the Starting Point



Notes: The dashed arrow represents the unique equilibrium path that leads to point B, governed by the dynamic system for θ, g and y. The solid line gives the relationship between $\theta(0)$ and $y(0)$ according to the relative factor demand equation (4.50) using $g = f(\theta)$.

and $y(0)$ according to the relative factor demand function. The dynamic behavior of θ and y is illustrated by the horizontal and vertical arrows, respectively.

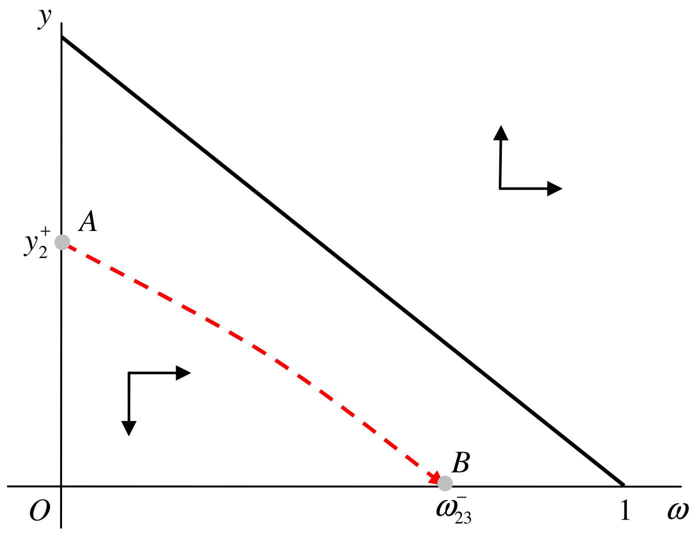
4.5.2 Simultaneous Use

If the economy shifts from the RUO to the SU regime, the reserve-to-extraction rate should be strictly positive at the beginning of the SU regime. Because of the continuity of relative factor prices and the innovation rate at T_{12}, the reserve-to-extraction rate should also be continuous at T_{12}, i.e. $y_{12}^{-} = y_2^{+}$. To determine the value of the reserve-to-extraction rate at T_{12}, we exploit the equilibrium condition that total extraction in the SU regime should be equal to the remaining stock at the beginning of this regime. Analogous to the derivation of (4.51) we use the relative demand equation (4.3) to obtain a differential equation for the reserve-to-extraction rate in terms of y and ω:

$$\dot{y} = \frac{L\nu\phi(1-\theta) + a\left[(1-\nu)(1+\phi) + \nu\phi(1-\theta)\right]\rho}{a\theta(1-\nu)(1-\omega)(1+\phi)} y - 1,$$

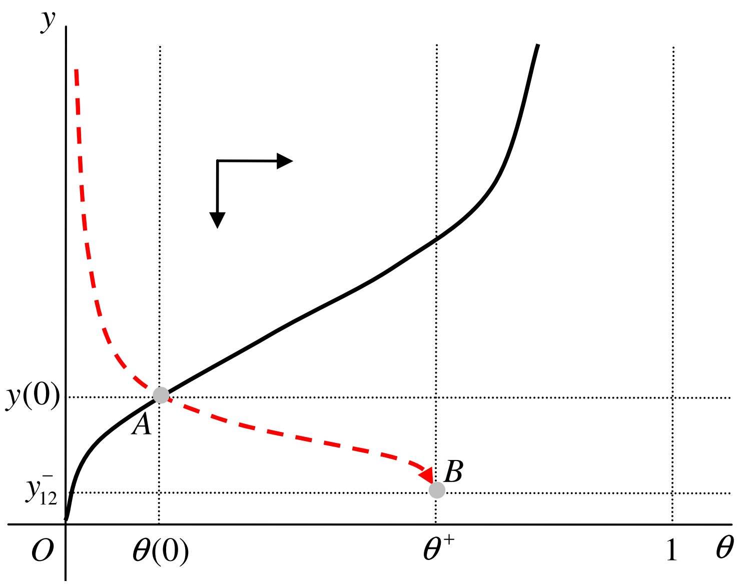
Together with the time path for ω, this differential equation for the reserve-to-

Figure 4.6: Determining the Reserve-to-Extraction Rate at the Regime Switch



Notes: The dashed arrow represents the unique equilibrium path that leads to point B, governed by the dynamic system for ω and y. The solid line is the $\dot{y} = 0$ locus, which gives combinations of ω and y such that y is constant over time.

Figure 4.7: Determining the Starting Point



Notes: The dashed arrow represents the unique equilibrium path that leads to point B, governed by the dynamic system for θ, g and y. The solid line gives the relationship between $\theta(0)$ and $y(0)$ according to the relative factor demand equation (4.50) using $g = f(\theta)$.

extraction rate gives rise to a unique equilibrium path in (ω, y)-space that leads to a zero reserve-to-extraction rate at the moment of the switch to the BTO regime (i.e. at $t = T_{23}$). The reserve-to-extraction rate at the switching moment then follows by evaluating y along this equilibrium path in (ω, y)-space at $\omega_2^+ = 0$. This point corresponds with the vertical intercept A of the dashed arrow in Figure 4.6. The solid line in the figure gives combinations of ω and y for which the reserve-to-extraction rate is constant over time. The dynamic behavior of ω and y is illustrated by the horizontal and vertical arrows, respectively.

Having determined $y_{12}^- = y_2^+$, as before we can use (4.51) to construct the unique path leading to this reserve-to-extraction rate at the end of the RUO regime, which together with (4.50) yields the start point $[\theta(0), y(0)]$, labeled A in Figure 4.7. The dashed arrow in the figure shows the equilibrium path leading to (θ^+, y_{12}^-) indicated by B, and the solid line depicts the relationship between the start values $\theta(0)$ and $y(0)$.

4.6 Numerical Illustration

In this section, we perform a simulation analysis to quantify the transitional dynamics of the model. We investigate two scenario: one benchmark in which simultaneous use of the resource and the backstop technology occurs for a considerable period of time and one alternative scenario in which the economy switches abruptly from the resource to the backstop technology without an intermediate era of hybrid energy generation. As a robustness check, we also provide simulation results for a formulation of our model in which the resource and the backstop technology are good instead of perfect substitutes.[17] We first calibrate the model and then present the simulation results.

4.6.1 Calibration

There is ample evidence that the elasticity of substitution between energy and man-made factors of production is less than unity. Koetse, de Groot, and Florax (2008) conduct a meta-analysis and find a point estimate for the cross-price elasticity between capital and energy in Europe of 0.338 in the short run and 0.475 in the long run. We take the average of these values to obtain $\sigma = 0.4$. According to

[17] For the substitution elasticity between the resource and the backstop technology, we choose $\gamma = 50$.

the estimation results of Roeger (1995), the markup of prices over marginal cost in the manufacturing sector of the U.S. economy over the period 1953-1984 varied from 1.15 to 3.14. To cover this range, we impose $\phi = 0.25$ in our benchmark scenario and $\phi = 2.33$ in the alternative scenario.[18] We set the production function parameter $\bar{\theta}$ and the rate of pure time preference ρ to 0.1 and 0.01, respectively. By imposing $\delta = 0.05$, we ensure that knowledge spillovers to the resource extraction sector are small. Labor supply L and the initial knowledge stock N_0 are normalized to 1 and 0.1, respectively.

The initial resource stock is chosen such that the initial share of resource expenditures in GDP θ_0 equals 8.8 percent, to match the average US energy expenditure share in GDP over the period 1970-2009 (U.S. Energy Information Administration, 2012).[19] We use the research productivity parameter a to obtain an initial consumption growth rate $\hat{C}_0$ of 1.7 percent, which is equal to the average yearly growth rate of GDP per capita in the US over the period 1970-2010 (The Conference Board, 2011). Our benchmark calibration implies an initial reserve-to-extraction rate of $y_0 = 52$ lies within the range of the reserve-to-production ratios for oil, natural gas, and coal in 2008 of 44, 58, and 127, respectively (U.S. Energy Information Administration, 2012). Initially, the ratio between the per unit of energy price of the backstop technology and the resource, $p_{H0}/p_{R0}N_0^{-\nu}$, amounts to 3.[20] In both scenarios, the current era in which energy generation relies on the non-renewable resource ends in roughly 4 decades.[21]

4.6.2 Results

Benchmark Calibration Figure 4.8 contains the phase diagram for the benchmark calibration and corresponds with Figure 4.4, which sketches the general case as discussed in Section 4.4.2. The fat dotted stable manifold starts just below the solid innovation locus, crosses the gray extraction isocline at the moment of

[18] In the alternative scenario, we adjust a and η to keep initial consumption growth and θ^+ unchanged.

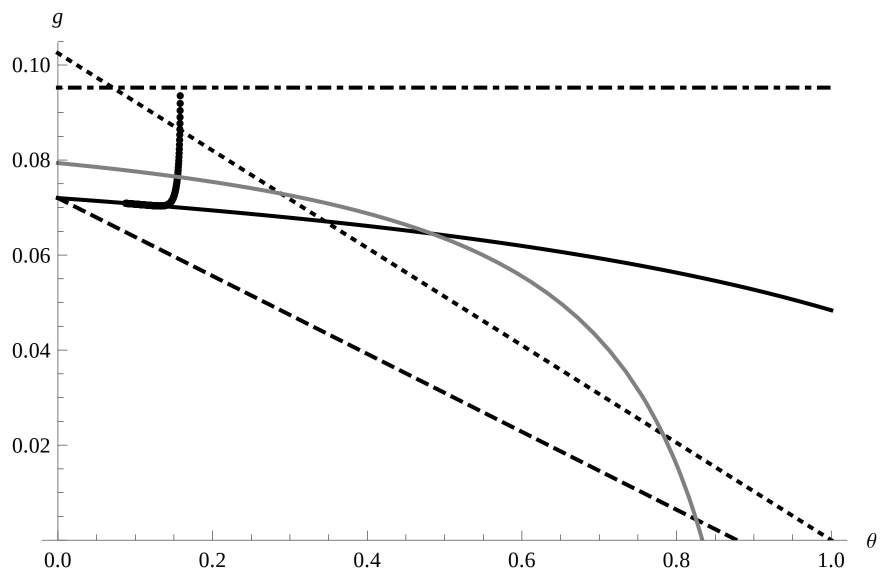
[19] We attribute energy expenditure entirely to resource expenditure, although part of the energy expenditure in the data consists of factor costs. Taking this distinction into account would imply a smaller initial resource expenditure share, without affecting the dynamics of the model.

[20] Using (4.3), this ratio is given by $\beta/\eta[\bar{\theta}/(1-\bar{\theta})]^{\frac{\sigma}{1-\sigma}}[(1-\theta(0))/\theta(0)]^{\frac{1}{1-\sigma}}$.

[21] In the benchmark and alternative calibration, the initial expenditures on innovation as a share of GDP are equal to 15 and 30 percent, respectively. Given that expenditure on innovation is the only investment possibility in the model, this number should be interpreted as the aggregate investment share in the economy.

peak-oil, and reaches the dash-dotted income share locus at the moment the economy switches to the simultaneous use regime. Accordingly, the innovation rate first decreases slightly over time, but starts to increase after the stable manifold has crossed the innovation locus. During the simultaneous use regime, the innovation rate declines gradually to the dotted $g_{23}^{-}(\theta)$ line and then jumps down to the dashed $g_3^{+}(\theta)$ line. This jump marks the beginning of the backstop technology only regime, during which the innovation rate remains constant over time.

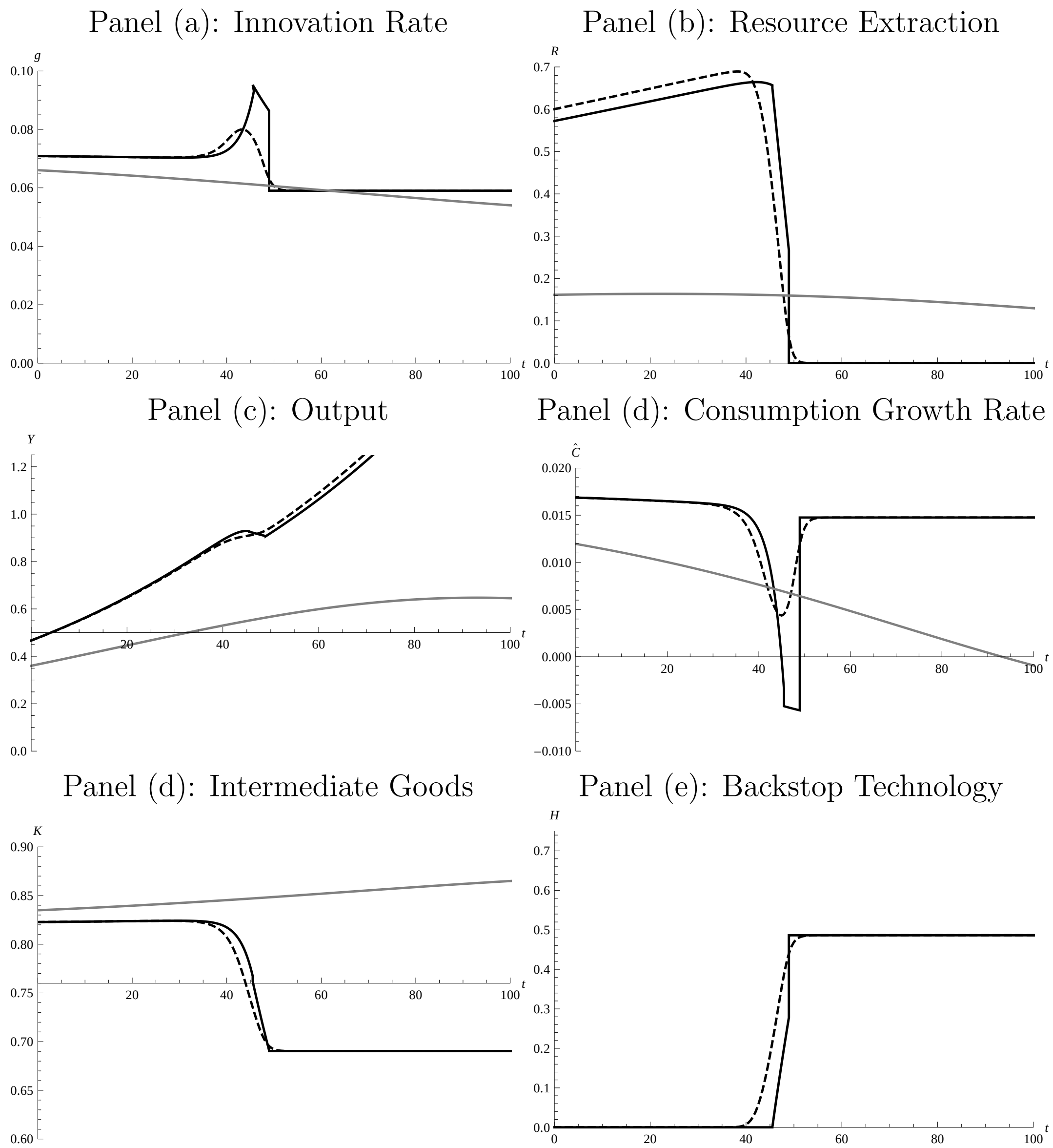
Figure 4.8: Phase Diagram (Benchmark Scenario)



Notes: The solid and dash-dotted line represent the innovation locus and income share locus, respectively. The fat dotted path represents the stable manifold. The gray line is the extraction isocline. The dashed and the dotted line represent the $g_3^{+}(\theta)$-line and the $g_{23}^{-}(\theta)$-line, respectively. The underlying parameters values are: $a = 2.5$, $\phi = 0.25$, $\delta = 0.05$, $\eta = 3$, $\rho = 0.01$, $\sigma = 0.4$, $\bar{\theta} = 0.1$, $\bar{\omega} = 0.9$, $\gamma = 50$, $L = 1$.

The solid line in Panel (a) of Figure 4.9 depicts the time path of the innovation rate in accordance with the analysis of the phase diagram in Figure 4.8. To illustrate the importance of taking the backstop technology into account, the gray line shows the innovation rate in a world similar to the benchmark economy, but without the availability of a backstop technology. In contrast to the benchmark case, innovation in such a world decreases monotonically over time and starts out lower. As a robustness check, the dashed line represents the time path in a model in which the resource and the backstop technology are good, but imperfect substitutes. The imperfect substitutes model yields time paths that, though smoother and with less pronounced extrema, are quite similar to those generated by our simpler model in which the resource and the backstop technology are perfect substitutes.

Figure 4.9: Transitional Dynamics (Benchmark Scenario)



Notes: The solid line represents scenario 1, in which a backstop technology that provides a perfect substitute for the resource is available. The gray line represents scenario 2, in which there is no backstop technology available. The solid line represents scenario 3, in which a backstop technology that provides a good, but imperfect substitute for the resource is available. Parameters are set to: $a = 2.5$, $\phi = 0.25$, $\delta = 0.05$, $\eta = 3$, $\rho = 0.01$, $\sigma = 0.4$, $\bar{\theta} = 0.9$, $\bar{\omega} = 0.9$, $\gamma = 50$, $L = 1$. The initial knowledge stock N_0 equals 0.1. The initial resource stock S_0 equals 30 in scenario 1 and 2 to obtain $\theta_0 = 0.912$ in scenario 1. In the third scenario, the initial resource stock is chosen such that $\theta_0 = 0.912$ and η is adjusted to obtain $\theta_\infty = \theta^+$.

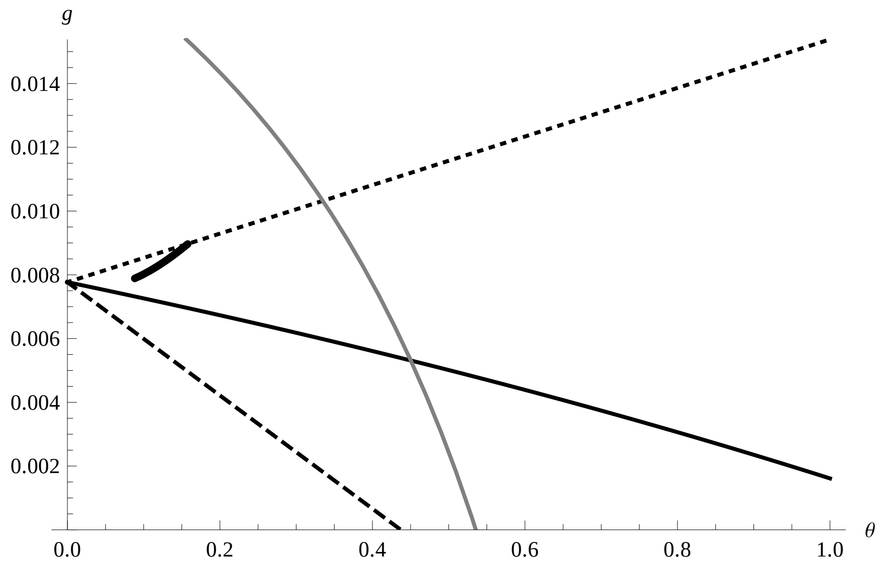
Panel (b) shows that extraction is increasing initially, peaks just before the economy switches to the simultaneous use regime and decreases subsequently until the stock is exhausted. Due to the finite exhaustion time, extraction starts out considerably higher than in the model without a backstop technology. Panels (c) and (d) depict output and its growth rate, respectively. Output growth is positive initially and in the long run, but becomes negative temporarily during the run-up to the introduction of the backstop technology. Consumption growth is decreasing over time during the first two regimes and then jumps up to a constant rate in the backstop technology only regime. Conversely, consumption growth is monotonically decreasing over time and eventually becomes negative in the model without a backstop technology.

As shown in Panel (d), the input of intermediate goods declines significantly during the end of the resource use only regime, to make free labor for backstop technology production. This effect is absent in the model without a backstop technology, resulting in an upward-sloping time path of intermediate goods. Backstop technology production is zero until the start of the simultaneous use regime, during which it increases quickly, as shown in Panel (e). At the end of this regime, backstop technology production jumps up to a constant level in the backstop technology only regime.

Alternative Calibration In the alternative scenario (with a larger price markup), the economy immediately jumps from the resource use only to the backstop technology only regime, without an intermediate period of simultaneous use. The phase diagram for the alternative calibration is shown in Figure 4.10, corresponding to the general case discussed in Section 4.4.1 and shown in Figure 4.3. The fat dotted stable manifold now starts above the innovation locus and does not intersect the gray extraction isocline. Hence, both the innovation rate and resource extraction are increasing over time until the end of the resource use only regime has been reached as the stable manifold hits the dotted g_{13}^{-} line. The energy income share now remains constant at θ^{+} and the innovation rate jumps down to the corresponding constant value at the dashed g_{3}^{+} line. This jump marks the beginning of the backstop technology only regime.

Figure 4.11 shows the transitional dynamics for the alternative calibration. Besides the absence of a simultaneous use regime, the most important differences are that the innovation rate and resource extraction are and remain increasing

Figure 4.10: Phase Diagram (Alternative Scenario)



Notes: The solid line represents the innovation locus. The fat dotted path represents the stable manifold. The gray line is the extraction isocline. The dashed and the dotted line represent the $g_3^+(\theta)$-line and the $g_{13}^-(\theta)$-line, respectively. The underlying parameters values are: $a = 65$, $\phi = 2.33$, $\delta = 0.05$, $\eta = 1.125$, $\rho = 0.01$, $\sigma = 0.4$, $\bar{\theta} = 0.9$, $\bar{\omega} = 0.1$, $\gamma = 50$, $L = 1$.

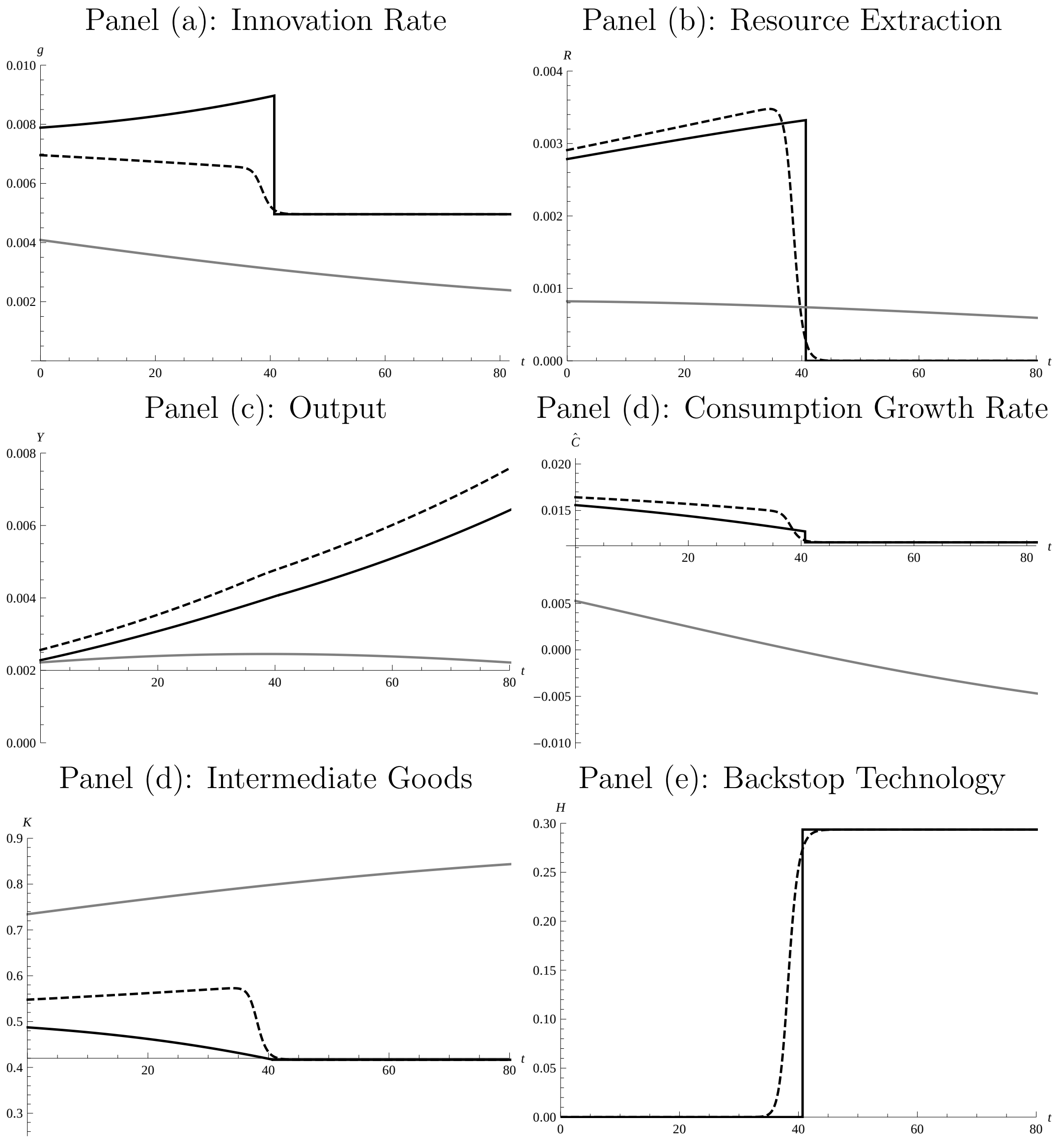
over time until the resource stock is exhausted, as shown in Panels (a) and (b).[22] Furthermore, Panels (c) and (d) reveal that the temporarily negative consumption growth has disappeared. Finally, there are some but no significant deviations from the benchmark scenario in the time paths for man-made inputs (Panels (d) and (e)): intermediate goods input now declines over time until the backstop technology is introduced and remains constant afterwards, and backstop technology production jumps up from zero to a constant positive number at the switching instant.

4.7 Conclusion

We have investigated the effects of the availability of a backstop technology on the time paths of resource extraction and the rate of technological progress, taking into account that natural resources and man-made inputs are poor substitutes

[22]Because the run-up to the backstop technology has already begun at $t = 0$ (the stable manyfold starts above the innovation locus), there is a discrepancy between the initial innovation rate in the perfect and imperfect substitutes model. When we decrease θ_0 far enough, this discrepancy disappears as in the benchmark scenario shown in Figure 4.9.

Figure 4.11: Transitional Dynamics (Alternative Scenario)



Notes: The solid line represents scenario 1, in which a backstop technology that provides a perfect substitute for the resource is available. The gray line represents scenario 2, in which there is no backstop technology available. The solid line represents scenario 3, in which a backstop technology that provides a good, but imperfect substitute for the resource is available. Parameters are set to: $a = 65$, $\phi = 2.33$, $\delta = 0.05$, $\eta = 1.125$, $\rho = 0.01$, $\sigma = 0.4$, $\bar{\theta} = 0.9$, $\bar{\omega} = 0.912$, $\gamma = 50$, $L = 1$. The initial knowledge stock N_0 equals 0.1. The initial resource stock S_0 equals 0.125 in scenario 1 and 2 to obtain $\theta_0 = 0.912$ in scenario 1. In the third scenario, the initial resource stock is chosen such that $\theta_0 = 0.912$ and η is adjusted to obtain $\theta_\infty = \theta^+$.

and that generation of energy with the backstop technology is costly. To this end, we introduce a non-renewable resource and a backstop technology in a simple general equilibrium endogenous growth model. The elasticity of substitution between energy and man-made inputs is assumed to be smaller than unity. The backstop technology can be used to produce a perfect substitute for the natural resource. Technological progress is driven by workers in R&D, who build upon previously generated knowledge. We solve the model analytically and develop a graphical apparatus to visualize its transitional dynamics and regime shifts. Moreover, we quantify the results by calibrating the model and performing a simulation analysis. The results are robust to relaxing the assumption of perfect substitutability between the resource and the backstop technology.

Our main findings can be divided into four categories: energy regimes, technological change, and resource extraction. Regarding the first category, we find that the economy experiences different regimes of energy generation. Initially, the economy relies exclusively on the natural resource. In the long run, the natural resource will be abandoned in favor of the backstop technology. In between these two regimes, depending on parameter values, there may exist an intermediate era during which the resource and the backstop technology are used simultaneously. This feature is noteworthy, because the model does not impose the convexities in resource extraction or backstop production costs that are normally required to obtain this result. The reason for the existence of a regime of simultaneous use is consumption smoothing: by introducing the backstop technology gradually during the simultaneous use regime, households effectively shift part of the resource wealth to the backstop era.

Second, the introduction of a backstop technology in the model crucially affects the shape of the time path of technological progress, measured by the rate of innovation. Instead of monotonically decreasing as it would be without the backstop technology, the rate of innovation exhibits a non-monotonic development over time: it first decreases gradually, but during the run-up to the introduction of the backstop technology it starts to increase in order to prevent a downward jump in consumption at the time of the shift to the backstop regime. Once the economy enters the backstop regime, the rate of innovation jumps down to its long-run value to free resources for production in the backstop sector. At any moment during the resource regime, the rate of innovation is strictly higher than it would be without the availability of a backstop technology.

Third, the introduction of the backstop technology has notable implications for the development of resource extraction over time. The resource extraction path does no longer eventually have to become downward-sloping. Depending crucially on the bias in technological change and the elasticity of substitution between energy and man-made inputs, the extraction path can be monotonically upward-sloping or downward sloping until exhaustion, or exhibit an internal maximum, known as ‘peak-oil’. Poor substitutability between the natural resource and man-made inputs, and technological change that is strongly resource-using lead to increasing resource extraction over time.

The most important direction for further research is the introduction of pollution from combustion and stock-dependent costs of extraction of the natural resource. In combination with the backstop technology these features make it interesting to compare the decentralized outcome to the social optimum, in order to shed light on optimal environmental policy. Another useful extension of the current analysis would be the introduction of separate R&D activities for man-made-inputs-augmenting and energy-augmenting technological change, so that the bias in technological progress becomes endogenous. This will be the topic of Chapter 6. First, Chapter 5 will examine in more detail the implications of imperfect substitutability between the non-renewable resource and the backstop technology.

4.A Appendix

This Appendix contains the derivations of the mathematical results in the main text of the chapter.

4.A.1 Final Output

In this section, we derive the relative factor demand equation (4.3). Profits of firms in the final output sector are given by:

$$p_Y \left[\bar{\theta} E^{\frac{\sigma-1}{\sigma}} + (1-\bar{\theta}) \left(\int_0^N k_j^{\beta} dj \right)^{\frac{\sigma-1}{\beta\sigma}} \right]^{\frac{\sigma}{\sigma-1}} - \int_0^N p_{Kj} k_j dj - p_R R - p_H H, \tag{A.4.1}$$

where E is defined in (4.2). The associated Lagrangian reads:

$$\begin{aligned} \mathcal{L} = p_Y & \left[\bar{\theta} E^{\frac{\sigma-1}{\sigma}} + (1-\bar{\theta}) \left(\int_0^N k_j^{\beta} dj \right)^{\frac{\sigma-1}{\beta\sigma}} \right]^{\frac{\sigma}{\sigma-1}} - \int_0^N p_{Kj} k_j dj - p_R R - p_H H \\ & + p_E \left(N^{\delta} R + N^{\xi} H \right). \end{aligned} \tag{A.4.2}$$

The optimality conditions are:

$$\frac{\partial \mathcal{L}}{\partial k_j} = p_Y \left[\bar{\theta} E^{\frac{\sigma-1}{\sigma}} + (1-\bar{\theta}) \left(\int_0^N k_j^{\beta} dj \right)^{\frac{\sigma-1}{\beta\sigma}} \right]^{\frac{\sigma}{\sigma-1}-1} (1-\bar{\theta}) K^{-\frac{1}{\sigma}} N^{\phi} \frac{1-\beta}{\beta} - p_K = 0, \tag{A.4.3a}$$

$$\frac{\partial \mathcal{L}}{\partial E} = p_Y \left[\bar{\theta} E^{\frac{\sigma-1}{\sigma}} + (1-\bar{\theta}) \left(\int_0^N k_j^{\beta} dj \right)^{\frac{\sigma-1}{\beta\sigma}} \right]^{\frac{\sigma}{\sigma-1}-1} \bar{\theta} E^{-\frac{1}{\sigma}} - p_E = 0, \tag{A.4.3b}$$

$$\frac{\partial \mathcal{L}}{\partial R} = p_E N^{\delta} - p_R \leqslant 0, \quad (p_E N^{\delta} - p_R) R = 0, \tag{A.4.3c}$$

$$\frac{\partial \mathcal{L}}{\partial H} = p_E N^{\xi} - p_H \leqslant 0, \quad (p_E N^{\xi} - p_H) H = 0, \tag{A.4.3d}$$

where we have used $p_{Ki} = p_{Kj} \equiv p_K$, $\forall\ i, j$. Combining (A.4.3a)-(A.4.3d) with $H = 0$ ($R = 0$) gives the first (second) row in (4.3). The third row of (4.3) follows from combining (A.4.3a)-(A.4.3d) with $p_H N^{-\xi} = p_R N^{-\delta}$ imposed.

4.A.2 Households

In this section, we first derive the flow budget constraint of the households. Subsequently, we solve the utility maximization problem that the households face.

4.A.2.1 Flow Budget Constraint

In this section we derive the flow budget constraint of the households (4.18). Total wealth is equal to $V = p_N N + p_R S$, so that the change in wealth is given by

$$\dot{V} = \dot{p}_N N + p_N \dot{N} + \dot{p}_R S + p_R \dot{S} = \dot{p}_N N + p_N \dot{N} + \dot{p}_R S - p_R R, \tag{A.4.4}$$

where the second equality uses (4.17). Nominal GDP can be written as

$$\begin{aligned} p_Y Y &= p_K K + p_R R + p_H H = \pi N + w L_K + p_R R + p_H H \\ &= r p_N N - \dot{p}_N N + w L_K + p_R R + p_H H, \end{aligned} \tag{A.4.5}$$

where the second and third equality use (4.7) and (4.13), respectively. Using (A.4.5) to substitute for $p_R R$ in (A.4.4), we obtain:

$$\dot{V} = p_N \dot{N} + \dot{p}_R S - p_Y Y + r p_N N + w L_K + p_H H = r p_N N + \dot{p}_R S + w L - p_Y Y, \tag{A.4.6}$$

where we have used (4.8), (4.9), (4.12), and (4.15) for the second equality. Using the definition of wealth again, we get (4.18).

4.A.2.2 Utility Maximization

The Hamiltonian associated with the optimization problem of the households reads:

$$\mathcal{H} = \ln(C) + \lambda_V \left[r(V - p_R S) + \dot{p}_R S + w L^S - p_C C \right], \tag{A.4.7}$$

where λ_V denotes the shadow price of wealth. The necessary first-order conditions for an optimum are given by:

$$\frac{\partial \mathcal{H}}{\partial C} = 0 \Rightarrow \frac{1}{C} - \lambda_V p_C = 0 \Rightarrow \hat{C} + \hat{p}_C = -\hat{\lambda}_V, \tag{A.4.8}$$

$$\frac{\partial \mathcal{H}}{\partial S} = 0 \Rightarrow -\lambda_V r p_R + \lambda_V \dot{p}_R = 0 \Rightarrow \hat{p}_R = r, \tag{A.4.9}$$

$$\frac{\partial \mathcal{H}}{\partial V} = -\dot{\lambda}_V + \rho \lambda_V \Rightarrow \lambda_V r = -\dot{\lambda}_V + \rho \lambda_V. \tag{A.4.10}$$

The transversality condition is given by (4.19). Combining (A.4.8) and (A.4.10) gives the Ramsey rule (4.20). The first-order condition (A.4.9) is the Hotelling rule (4.21).

4.A.3 Proof of Proposition 4.1

By substituting the labor market equilibrium (4.16) with $\omega = 0$ imposed into (4.14), find expression (4.24) for the return to innovation in the RUO regime. We use the expenditure share definitions in (4.4) to rewrite the first line of the relative demand function (4.3):

$$\frac{\theta}{1-\theta} = \left(\frac{p_R}{p_K}\right)^{1-\sigma} \left(\frac{\bar{\theta}}{1-\bar{\theta}}\right)^{\sigma} N^{\nu(1-\sigma)} \Rightarrow \hat{\theta} = (1-\theta)(1-\sigma)\left[r - \hat{w} + \nu g\right]. \quad \text{(A.4.11)}$$

This completes the derivation of expression (4.22) in Proposition 4.1. To obtain the second expression in the proposition, we first differentiate the labor market equilibrium condition to get:

$$\hat{K} = -\frac{\dot{g}}{\frac{L}{a} - g}. \quad \text{(A.4.12)}$$

By converting the energy income share definition (4.4) into growth rates while using the intermediate goods price (4.6) and the Ramsey rule (4.20), we obtain:

$$\hat{\theta} = -\frac{1-\theta}{\theta}\left[\hat{w} + \hat{K} - (r-\rho)\right]. \quad \text{(A.4.13)}$$

Combining (A.4.11), (A.4.12), and (A.4.13), we find (4.23) in Proposition 4.1. □

4.A.4 Properties of Isoclines and Differential Equations

This section derives some properties of the isolines and the differential equations for θ and g. From (4.25)-(4.26), we derive the first-order derivatives of the isoclines with respect to θ:

$$\frac{\partial(g|_{\dot{\theta}=0})}{\partial\theta} = 0, \quad \text{(A.4.14)}$$

$$\frac{\partial(g|_{\dot{\theta}=0})}{\partial\theta} = -\frac{(1-\sigma)\left\{\frac{L}{a}(1+\phi)\phi\left[1-\frac{1+\delta}{1+\phi}\right] + (1-\delta)\rho\right\}}{[1+\phi-(1+\delta)\theta(1-\sigma)]^2} < 0, \quad \text{(A.4.15)}$$

where the inequality follows from $\nu > 0 \Leftrightarrow 1+\phi > 1+\delta$. For the first-order derivatives of the differential equations (4.22) and (4.23) with respect to g, we have

$$\frac{\partial\dot{\theta}}{\partial g} = -\theta(1-\theta)(1-\sigma)(1+\delta) < 0, \quad \text{(A.4.16)}$$

$$\frac{\partial\dot{g}/[L/a-g]}{\partial g} = 1+\phi-\theta(1-\sigma)(1+\delta) > 0, \quad \text{(A.4.17)}$$

where the inequality follows from $\nu > 0 \Leftrightarrow 1+\delta < 1+\phi$.

4.A.5 Steady States

This section shows that point B in Figure 4.2 is the only attainable steady state of the model without a backstop technology that satisfies the transversality condition (4.19).

Proposition 4.8. *The only attainable internal steady state of the model without a backstop technology that satisfies the transversality conditions is given by point B in Figure 4.2. Using asterisks (*) to denote steady state values of this model, the other three steady states of the model satisfy:*

$$g^* = \frac{L}{a}, \quad \theta^* = 1, \tag{A.4.18a}$$

$$g^* = \frac{L}{a}, \quad \theta^* = 0, \tag{A.4.18b}$$

$$g^* = \frac{\phi}{1+\phi}\frac{L}{a} - \frac{\rho}{1+\phi}, \quad \theta^* = 0. \tag{A.4.18c}$$

Proof. The first two steady states (A.4.18a) and (A.4.18b) do not satisfy the transversality condition, because substitution of $K^* = L - ag^* = 0$ into (4.24) implies $(r - \hat{w})^* = -g^* < 0$ and the transversality condition (4.19) in growth rates requires:

$$\lim_{t\to\infty} = \hat{p}_N(t) + \hat{N}(t) - r(t) \leqslant 0 \Rightarrow \lim_{t\to\infty} r(t) - \hat{w}(t) \geqslant 0, \tag{A.4.19}$$

where the second equality uses (4.12) and (4.21). Hence, the two steady states with $(r - \hat{w})^* = -g^* < 0$ do not satisfy the transversality condition. Steady state (A.4.18c) is located at the intersection of the innovation locus with the $\theta = 1$ line, and below the income share locus in (θ, g)-space. It is immediately clear from the dynamics around this point in Figure 4.2 ($\dot{\theta} < 0$) that this steady state cannot be attained. The economy can only be situated here if there is an infinite amount of oil available from the beginning (so that $\theta^* = 1$), which is impossible. Point B in Figure 4.2 satisfies the transversality condition, as $(r - \hat{w})^* = \rho > 0$ in this equilibrium. □

4.A.6 Expressions for Δ's

The expressions for the differences defined in 4.3.1 are given by:

$$\Delta_1 \equiv g|_{\hat{R}=0,\theta=0} - g|_{\dot{g}=0,\theta=1} = \frac{\phi\frac{L}{a}\left[1+\phi-(1+\delta)\right] - \rho\left[\frac{1+\phi}{1-\sigma} - 2(1+\delta)\right]}{(1+\delta)\left[1+\phi-(1+\delta)(1-\sigma)\right]},$$

$$\Delta_2 \equiv g|_{\hat{R}=0,\theta=0} - g|_{\dot{g}=0,\theta=0} = \phi\frac{L}{a}\frac{1+\phi-(1+\delta)}{(1+\delta)(1+\phi)} - \rho\frac{1+\phi-(1+\delta)(1-\sigma)}{(1+\delta)(1-\sigma)(1+\phi)}.$$

4.A.7 Proof of Proposition 4.2

In the SU regime, the effective prices of the resource and the backstop technology must be equal, as in the third line of (4.3):

$$p_H N^{-\xi} = p_R N^{-\delta}. \tag{A.4.20}$$

Substitution of $p_E = p_H N^{-\xi}$ and (A.4.20) into the third line of the relative demand function (4.3) and by using $p_K/p_H = \eta(1+\phi)$ from (4.6) and (4.9) gives

$$\frac{\theta}{1-\theta} = [(1+\phi)\eta]^{\sigma-1}\left(\frac{\bar{\theta}}{1-\bar{\theta}}\right)^{\sigma} N^{(\phi-\xi)(1-\sigma)}, \tag{A.4.21}$$

which implies $\theta = \theta_{12}^{+}$ under the assumption that $\xi = \phi$ and therefore proofs the first part of the proposition. To proof the second part, we convert (A.4.20) into growth rates:

$$\hat{p}_H - \xi g = \hat{p}_R - \delta g \Rightarrow r - \hat{w} + \nu g = 0, \tag{A.4.22}$$

where the latter expression uses (4.9) and (4.21).[23] We use (4.4) to rewrite the third row of relative demand function (4.3) as

$$\frac{\theta}{1-\theta} = \left(\frac{p_E}{p_K}\right)^{1-\sigma}\left(\frac{\bar{\theta}}{1-\bar{\theta}}\right)^{\sigma} N^{\phi(1-\sigma)} \Rightarrow \hat{\theta} = (1-\sigma)(1-\theta)(r - \hat{w} + \nu g), \tag{A.4.23}$$

where we have made use of (4.6), (4.21) and $\hat{p}_E = \omega(\hat{p_R} - \delta g) + (1-\omega)(\hat{p}_H - \xi g)$. The combination of (A.4.22) and (A.4.23) shows that the income share of energy is constant in the SU regime. Substituting (A.4.22) into (4.14), we find

$$-\nu g = \phi\frac{K}{a} - g. \tag{A.4.24}$$

Using (4.4), (4.6), (4.20), (4.21) and $\hat{\theta} = 0$ together with (A.4.24), we obtain:

$$\hat{g} = \hat{K} = -\nu g - \rho, \tag{A.4.25}$$

which gives rise to the differential equation in Proposition 4.2. □

[23] The parameter ν equals $\xi - \delta$ reflecting our assumption that technological progress is Hicks neutral in the long run.

4.A.8 Proof of Proposition 4.3

Using $p_K/p_H = \eta(1+\phi)$ from (4.6) and (4.9), the relative factor demand function (4.3) gives

$$\frac{H}{K} = [\eta(1+\phi)]^{\sigma-1}\left(\frac{\theta_3^+}{1-\theta_3^+}\right) = \left(\frac{\bar{\theta}}{1-\bar{\theta}}\right)^{\sigma}, \tag{A.4.26}$$

which can be solved for θ to obtain θ_3^+. Combining the income share definition (4.4), the innovation return (4.14), labor market equilibrium (4.16), the Ramsey rule (4.20), and the relative demand function (A.4.26), we find a differential equation for the innovation rate:

$$\dot{g} = -\left(\frac{L}{a} - g\right)\left[\phi\left(\frac{1-\theta_3^+}{\theta_3^+(1+\phi)+1-\theta_3^+}\right)\left(\frac{L}{a} - g\right) - g - \rho\right]. \tag{A.4.27}$$

Because this differential equation is unstable in g, the innovation rate immediately settles down at its steady state value given by the second expression in Proposition 4.3. □

Chapter 5

Fossil Fuels, Backstop Technologies, and Imperfect Substitution

> "*All progress is precarious, and the solution of one problem brings us face to face with another problem.*"
>
> — Martin Luther King, Jr. (1929-1968)

5.1 Introduction

Technical progress and backstop technologies are now generally considered to be the solution to the sustainability problem raised by the Club of Rome in their alarming report about the limits to growth on our finite planet (Meadows et al., 1972): the economic consequences of the finite availability of natural resources can be mitigated by increasing the productivity of these resources or by finding substitutes that can replace them. However, although this putative *panacea* releases the economy from the physical scarcity problem, it may also have adverse effects on sustainability by affecting environmental quality. In particular, the literature on the 'Green Paradox' has shown that the introduction of a backstop technology might lead to faster depletion of natural resources, like fossil fuels, and therefore to an increase in current environmental pollution (cf. Sinn, 2008; Sinn, 2012). For reasons of simplicity, these studies assume, as we did in Chapter 4, that the backstop technology is capable of producing a *perfect* substitute for fossil fuels. The current chapter contributes to the literature by generalizing the analysis to the more realistic case in which the backstop technology delivers a good, but *imperfect* substitute for non-renewable natural resources. In so doing, we are able to scrutinize the role of the degree of substitutability on the consequences that the introduction of a backstop technology has for production growth and resource extraction. While this chapter does not incorporate global warming on environmental damages directly, it does lay a foundation for a better understanding of the dynamic pattern of fossil fuel extraction in economies that are undergoing a transition towards the use of alternative energy sources. This foundation is essential, because the dynamic pattern of fossil fuel extraction coincides with the pattern of carbon emissions.

There are currently no technologies available that will be able to provide a perfect substitute for fossil fuels on an economy-wide level. New electricity production techniques like nuclear fission, nuclear fusion, solar power, hydro power, and wind power all suffer from a relatively low energy concentration: the storage of the generated electricity uses much more space than fossil fuels would to carry the same amount of energy, which makes them less suitable for the transport sector (Sinn, 2008; Sinn, 2012, p. 177). Wind and solar power have the additional problem of being less reliable than fossil fuels, because of their intermittent energy supply. At the moment, biofuels are the closest substitute for fossil fuels. Biofuels, however, cannot replace fossil fuels entirely. In aviation, for instance, biofuels have to be blended with conventional petroleum because otherwise they break down and leave deposits under the high temperatures of aircraft fuel systems (Hileman et al., 2009, p. 65). Moreover, the energy supply capacity of biofuels is limited and the production costs are convex in the level of energy generated (Sinn, 2008; Sinn, 2012, p. 177). To put it into perspective, satisfying the current global energy demand from the transport sector alone purely with biofuels would already require the total agricultural area available on earth (cf. International Energy Agency, 2006, p. 289).

The transition from extraction of fossil fuels to alternative energy technologies is inevitable given the finiteness of reserves. This transition has started already, but only to a small degree—not enough to provide us with answers to fundamental economic questions: Will the transition to clean energy be abrupt as predicted by existing models? To what extent will the time path of innovation be affected? How important is the degree of substitutability between the backstop technology and the non-renewable resource? This chapter addresses these questions in the simplest possible model. By taking the imperfect substitutability between new technologies and fossil fuels into account, we are able to analyze the consequences of this feature for the energy transition. Our main findings are as follows. If the elasticity of substitution is large enough, the future introduction of the backstop technology will take place abrupt and the outcomes of the model are in line with the results obtained in models with perfect substitution. If substitution possibilities are more limited, however, we find a gradual transition from fossil fuels to the backstop technology. The lower the elasticity of substitution between fossil fuels and the backstop technology, the more prolonged will be the period during which a non-negligible amount of both energy sources is used simultaneously. In line with the literature on the Green Paradox, the availability of a backstop technology leads to more aggressive extraction of the resource in the short run. Using the terminology of Gerlagh (2011), our model thus gives rise to a 'Weak Green Paradox'.[1] At the same time, however, we also find a 'Weak Green Orthodox': an invention that increases the substitutability between the backstop technology and the non-renewable resource leads to a short-run decrease in resource extraction. Furthermore, we find that the time profile of innovation is non-monotonic if the elasticity of substitution between the resource and the backstop technology is large enough: innovation first decreases slightly over time, it increases during the early part of the energy transition and then declines to a lower long-run level as the energy transition is completed. Finally, we find that the long-run outcomes of the model are not affected by the substitution possibilities in the energy sector as long as the elasticity of substitution exceeds unity.[2]

Our analysis builds upon the so-called Dasgupta-Heal-Solow-Stiglitz (DHSS) model, which integrates non-renewable resources into the neoclassical growth framework. It consists of the seminal contributions of Dasgupta and Heal (1974), Solow 1974a; 1974b, and Stiglitz 1974a; 1974b.[3] In the analysis of Dasgupta and Heal (1974) and in the related work of Heal (1976), Hoel (1978) and Dasgupta and Stiglitz (1981), the available backstop technology is assumed to provide a perfect substitute for the resource. As a result, energy generation will initially rely completely on the resource. Over time, the relative price of the resource compared

[1]In the terminology of Gerlagh (2011), a Weak Green Paradox arises if '(the anticipation of) a cheaper clean energy technology increases current emissions'.

[2]Long-run outcomes are dramatically affected if the elasticity of substitution between the resource and the backstop drops below unity, as the model would then converge to a different steady state.

[3]Recently, Benchekroun and Withagen (2011) have developed a technique to calculate the closed form solution to the DHSS model.

to the backstop technology increases and the backstop is adapted once prices are equalized. More recent contributions also assume perfect substitutability between the resource and the backstop technology (cf. Tsur and Zemel, 2003, 2005; Valente, 2011; Van der Ploeg and Withagen, 2012). By assuming that the backstop technology is characterized by increasing instead of constant marginal production costs, Hung and Quyen (1993), Tahvonen and Salo (2001), and Chakravorty, Leach, and Moreaux (2012) obtain simultaneous use of the resource and the substitute in their theoretical models. However, these analyses still rely on perfect substitution between the resource and the backstop technology.

There are two notable exceptions to the ubiquitous perfect substitution assumption in the literature on the transition from resources to backstop technologies.[4] The first one is Michielsen (2011), who studies climate policy in a framework of imperfect substitution between a non-renewable resource and two backstop technologies: a clean and a dirty one. His focus, however, is on the effects of climate policy consisting of taxes on fossil fuels and cost reductions of the clean backstop. Moreover, the analysis takes place in a partial equilibrium setting, leaving no room for output growth and changes in the energy demand function over time. The other study that takes imperfect substitution into account, is Long (2012). He shows that if the existing degree of substitutability between the resource and the backstop technology is moderate or high, a technological change that further increases the degree of substitutability may cause fossil fuel producers to anticipate lower demand in the future, which encourages them to increase extraction immediately. Accordingly, Long (2012) predicts a Weak Green Paradox. The difference with the Weak Green Orthodox that we obtain occurs because Long (2012) uses a partial equilibrium analysis and imposes linear demand functions for the resource and the backstop technology.

In this chapter, we develop the simplest possible general equilibrium model that incorporates poor substitution between energy and man-made factors of production on the one hand, and imperfect substitution between non-renewable resources and the backstop technologies on the other.[5] A dynamic general equilibrium setting is required to account for the linkages between investment in innovation, expenditure on a backstop energy technology, extraction of fossil fuels, and consumption over time. Moreover, by allowing for investment in R&D, we extend the

[4] Smulders and van der Werf (2008) also allow for imperfect substitution in a model with resource extraction, but in their analysis both resources are non-renewable.

[5] For the perfect substitutes case, see Chapter 4.

analysis beyond the simple ‘cake-eating problem’ therewith introducing a possibility of obtaining long-run growth in output. In contrast to the DHSS model, we choose for investment in knowledge instead of in physical capital to orient our analysis towards the long run, when technical change rather than capital accumulation is the determinant of output growth. Hence, the essential trade-off between current and future consumption that is at the heart of modern growth theory, is captured in our model by the allocation of a primary input, i.e. labor, over production of consumption goods and investment in innovation and by the trade-off between using more fossil fuel today versus leaving more resources underground to extract in the future. For reasons of simplicity, the final good and factor markets are characterized by perfect competition. However, the market for intermediate goods is assumed to be monopolistically competitive, because the non-rivalry of knowledge would lead to zero R&D under perfect competition Romer (1990).

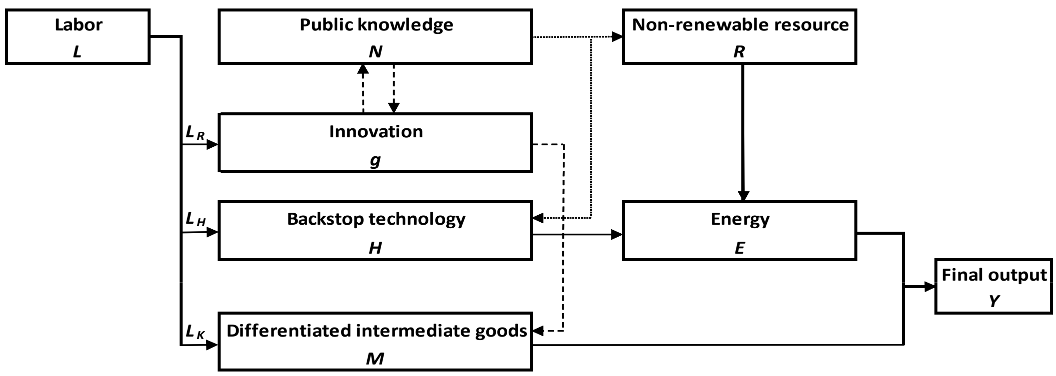
The structure of the model is as follows. Final output is produced with intermediate goods and energy, according to a constant elasticity of substitution (CES) specification. The production of intermediate goods requires labor. Energy is derived from a non-renewable natural resource that can be extracted at zero costs and from a costly backstop technology that uses labor. The elasticity of substitution between the resource and the backstop technology is assumed to be larger than unity. In line with the empirical evidence, the elasticity of substitution between energy and intermediate goods is assumed to be smaller than unity Koetse, de Groot, and Florax (2008). Technological progress in the model is driven by labor allocated to R&D directed at the invention of new intermediate goods. We assume knowledge spillovers from the stock of invented intermediate goods to the resource sector and the backstop sector. We solve analytically for the steady state of the model and we develop a graphical apparatus to study its transitional dynamics. Finally, we calibrate and simulate the model to study the behavior of the economy for different degrees of substitutability between the resource and the backstop technology. Throughout the chapter, our focus will be on the decentralized market equilibrium. Although we do not explicitly include pollution from the combustion of fossil fuels, the market equilibrium does not coincide with the social optimum. The reasons are (i) the monopolistic competition in the intermediate goods sector, leading to lower than optimal production of existing varieties, and (ii) the intertemporal knowledge spillover, implying a sub-optimally low level of investment in the invention of new varieties.

The remainder of this chapter is structured as follows. Section 2 describes the model. Section 3 discusses the solution procedure. Section 4 characterizes the transitional dynamics and describes the calibration of the model. Section 5 discusses the main results and Section 6 concludes.

5.2 The Model

This section describes the model in detail. It first discusses the production and energy generation sectors. Subsequently, the process of knowledge generation through research and development will be specified and market equilibrium conditions will be presented. Finally, the behavior of households in the model will be described. Figure 5.1, which is identical to Figure 4.1, gives a schematic representation of the goods, factor, and knowledge flows in the model.

Figure 5.1: Schematic representation of goods, factor, and knowledge flows



5.2.1 Final Good Sector

Final output Y is produced with energy E and an intermediate input M, according to the following constant elasticity of substitution (CES) specification:

$$Y = \left[\bar{\theta}E^{\frac{\sigma-1}{\sigma}} + (1-\bar{\theta})M^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{5.1}$$

where $0 < \sigma < 1$ denotes the elasticity of substitution between intermediate inputs and energy, and $0 < \bar{\theta} < 1$ regulates the relative productivity of the two inputs. To simplify the analysis, we abstract from the accumulation of physical capital.

The intermediate input M is a CES aggregate of different varieties of machines k:

$$M = \left(\int_0^N k_j^{\beta} dj \right)^{\frac{1}{\beta}}, \tag{5.2}$$

where $N > 0$ is the mass of intermediate input producers. The elasticity of substitution between the different varieties is equal to $1/(1 - \beta)$. Each firm in the intermediate input sector produces one specific machine variety. Machine producers are assumed to be identical, so that in equilibrium the producer of each machine variety j will choose the same amount of output, so that (5.2) reduces to

$$M = N^{\phi} K, \tag{5.3}$$

where $K \equiv Nk$ represents the total input of intermediates and $\phi \equiv (1 - \beta)/\beta$ is a measure of the gains from specialization: while keeping aggregate intermediate goods K constant, the intermediate input M rises with the number of varieties N because of increased specialization possibilities in the use of intermediate goods (cf. Ethier, 1982; Romer, 1987, 1990).

Final goods producers maximize profits in a perfectly competitive market. They take their output price p_Y, the prices of intermediate goods p_{K_j}, the energy price p_E as given. Relative demand for intermediate goods and energy is therefore given by:

$$\frac{K}{E} = \left(\frac{p_E}{p_K} \right)^{\sigma} \left(\frac{1 - \bar{\theta}}{\bar{\theta}} \right)^{\sigma} N^{-\phi(1-\sigma)}. \tag{5.4}$$

5.2.2 Energy Generation Sector

The generation of energy E uses the non-renewable resource R and the backstop technology H, according to the following production function:

$$E = \begin{cases} \left[\bar{\omega}(A_H H)^{\frac{\gamma-1}{\gamma}} + (1 - \bar{\omega})(A_R R)^{\frac{\gamma-1}{\gamma}} \right]^{\frac{\gamma}{\gamma-1}} & \text{if } \gamma \neq 1 \\ (A_H H)^{\bar{\omega}} (A_R R)^{1-\bar{\omega}}. & \text{if } \gamma = 1 \end{cases}, \tag{5.5}$$

where $0 < \gamma \ll \infty$ denotes the elasticity of substitution between the non-renewable resource and the backstop technology, $0 < \bar{\omega} < 1$ regulates the relative productivity of the two inputs, and $A_H > 0$ and $A_R > 0$ are productivity indexes. The energy generation function (5.5) captures three scenarios regarding the ease with which the backstop technology can replace the non-renewable resource as a source of energy. In the first scenario with $0 < \gamma < 1$, the resource and the backstop technology are *gross complements*. In this case, the resource and the backstop technology are poor substitutes, equilibrium resource expenditure as a share of total energy expenditures increases if the relative supply of the resource, R/H, decreases, and the non-renewable resource is necessary for the generation of energy.[6] The second scenario is characterized by $\gamma \to 1$, so that the energy production function changes to the Cobb-Douglas specification in the second row of (5.5). In this scenario, the expenditure share of the resource is fixed and equal to $1-\bar{\omega}$ and the resource is still necessary. The third scenario with $1 < \gamma \ll \infty$ describes the case in which the resource and the backstop technology are *gross substitutes*. In this case, the resource and the backstop are good substitutes, and the expenditure share of the resource shrinks if the relative supply of the resource decreases. Moreover, the resource is no longer necessary for the generation of energy.

Besides the discussed scenarios, there are also two extreme cases: no substitution and perfect substitution between the resource and the backstop technology. In terms of the elasticity of substitution, these cases correspond to $\gamma \to 0$ and $\gamma \to \infty$, respectively. Taking the appropriate limits of γ in (5.5), we find that the energy generation function for the extreme cases read:

$$E = \begin{cases} \min\{\bar{\omega}A_H H, (1-\bar{\omega})A_R R\}. & \text{if } \gamma \to 0 \\ \bar{\omega}A_H H + (1-\bar{\omega})A_R R. & \text{if } \gamma \to \infty \end{cases} . \tag{5.6}$$

According to the Leontief specification in the first row of (5.6), the resource and the backstop technology (corrected for productivity differences) are used in fixed proportions: a decrease in the input of the relatively scarce factor irrevocably leads to a decline in energy generation. In the other extreme case, represented by the linear function in the bottom row of (5.6), a decrease in one of the inputs can always be offset by a one-for-one increase in the other input to keep the level of generated energy constant. Moreover, whereas it can be shown that in the scenarios with $\gamma \ll \infty$ the resource and the backstop technology will be used simultaneously in equilibrium, in this perfect substitution scenario only the cheapest of the two will be deployed. Simultaneous use is only possible if prices (corrected for productivity differences) are equal.

The scenarios with $0 \leqslant \gamma < 1$ would not add much to the existing literature that does not consider the existence of a backstop technology, because of similar

[6] As noted in Chapter 1, an input is labeled necessary if output would be zero without a positive amount of this input (Dasgupta and Heal, 1979).

long-run dynamics that are dominated by the ever decreasing input of the necessary non-renewable resource. Therefore, we focus on the case where $\gamma \geqslant 1$. As discussed, for reasons of analytical simplicity, much of the existing literature investigates the extreme scenario of perfect substitution. However, in reality it is unlikely that a perfect substitute for non-renewable resources, like oil, exists or will be invented. For that reason, in this chapter we explore the more general case of imperfect substitutes. Moreover, we want to look at different values for the elasticity of substitution between the resource and the backstop technology, so that we focus on the general case of gross substitutes, instead of on the specific Cobb-Douglas case in which $\gamma = 1$. Therefore, in our analysis we use the specification in the top row of (5.5) with $1 < \gamma \ll \infty$, corresponding with the third scenario that we have discussed in this section.

The market for energy is characterized by perfect competition. Therefore, suppliers of energy take the prices of the non-renewable resource and the substitute as given. Relative demand from the energy sector for both inputs is given by:

$$\frac{R}{H} = \left(\frac{1-\bar{\omega}}{\bar{\omega}}\right)^{\gamma} \left(\frac{p_H}{p_R}\right)^{\gamma} \left(\frac{A_R}{A_H}\right)^{\gamma-1}, \tag{5.7}$$

where p_H and p_R denote the prices of the backstop technology and the non-renewable resource, respectively.

5.2.3 Intermediate Goods Sector

Each firm in the intermediate goods sector produces a unique machine variety. Before a firm is allowed to produce a certain machine, it first has to buy a patent on the market. The production function for intermediate goods is given by:

$$k_j = l_{K_j} \Rightarrow K = L_K, \tag{5.8}$$

where l_{K_j} denotes labor demand by firm j, which is equal for each firm so that $l_{K_j} = l_K$, and $L_K \equiv Nl_K$ is aggregate labor demand by the intermediate goods sector. The different machine varieties are imperfect substitutes for each other. As a result, the intermediate goods market is characterized by monopolistic competition. Each producer maximizes profits and faces a demand elasticity of $1/(1-\beta)$ so that all firms charge the same price of a mark-up $1/\beta$ times marginal cost, which equals the wage rate w:

$$p_K = \frac{w}{\beta}. \tag{5.9}$$

Because of this mark-up, firms in the intermediate goods sector make profits, which are used to cover the costs of obtaining a patent. Combining (5.8) and (5.9), profits for each firm are given by:

$$\pi = p_K k - wk = \phi \frac{wK}{N}. \tag{5.10}$$

In equilibrium, the price of a patent will be equal to the present discounted value of the profits generated by the corresponding machine variety.

5.2.4 Backstop Technology Sector

Firms in the backstop technology sector use labor to produce the substitute for the non-renewable resource, according to the simple production function

$$H = \eta L_H, \tag{5.11}$$

where H and L_H denote aggregate output of and labor demand from the backstop technology sector. The market for the substitute is perfectly competitive. Therefore, the price of one unit of the substitute equals its marginal cost:

$$p_H = \frac{w}{\eta}. \tag{5.12}$$

5.2.5 Research and Development

By undertaking research and development (R&D), intermediate firms invent new intermediate good varieties. Following Romer (1990), we assume that the stock of public knowledge evolves in accordance with the number of invented intermediate goods. New varieties are created according to:

$$\dot{N} = \frac{1}{a} L_R N, \tag{5.13}$$

where L_R denotes labor allocated to research and a is a productivity parameter. The right hand side of (5.13) features the stock of public knowledge, to capture the 'standing on shoulders effect': researchers are more productive if the available stock of public knowledge is larger (cf. Romer, 1990). We define the innovation rate as

$$g \equiv \frac{\dot{N}}{N}. \tag{5.14}$$

Free entry of firms in the research sector implies that whenever the cost of inventing a new variety, wa/N, is lower than the market price of a patent, p_N, entry of firms in the research sector will take place until the difference is eliminated. As a result, free entry gives rise to the following condition:

$$aw/N \leqslant p_N \qquad \text{with equality (inequality) if } g > 0 \ (g = 0). \tag{5.15}$$

As argued before, the market price of a patent will be equal to the present discounted value of the profits generated by the corresponding machine variety:

$$p_N(t) = \int_t^{\infty} \pi(z) e^{\int_t^z r(s)ds} dz, \tag{5.16}$$

where r denotes the nominal interest rate. Differentiating (5.16) with respect to time, we find the following Hamilton-Jacobi-Bellman equation:

$$\pi + \dot{p_N} = rp_N, \tag{5.17}$$

which can be interpreted as a no-arbitrage condition that requires investors to earn the market interest rate on their investment in patents. By combining (5.9), (5.10), (5.14), (5.15), and (5.17), we obtain an expression for the return to innovation:

$$r = \phi \frac{K}{a} - g + \hat{w}, \text{ if } g > 0, \tag{5.18}$$

where hats denote growth rates. The return to innovation depends positively on K, because of a market size effect and negatively (positively) on g ($\hat{w}$), because fast innovation (high wage growth) implies a rapidly decreasing (increasing) patent price. The parameters a and β both have a negative effect on the return to innovation, because they are related negatively to the productivity of researchers and the mark-up on the price of intermediate goods, respectively.

The increase of the number of varieties enhances the aggregate productivity of intermediate goods, as shown by (5.3). We assume that this process of knowledge accumulation also generates spillovers to the backstop sector and the resource sector, by using the following specifications for the productivity indexes of the energy inputs:

$$A_R = N^{\phi_R}, \tag{5.19a}$$

$$A_H = N^{\phi_H}. \tag{5.19b}$$

Below we will show that the economy will asymptotically converge to a regime in which energy generation relies exclusively on the backstop technology. Given that we are not interested in this regime *per se*, but merely in the transition from the non-renewable resource to the backstop technology, we simplify the analysis by imposing $\phi_H = \phi$, so that the final regime will be a steady state in which the innovation rate and the income shares are constant. Furthermore, to be on the conservative side, we assume only moderate knowledge spillovers to the resource sector, by imposing $\phi_R < \phi$. Assumption A.5.18a summarizes the discussion about knowledge spillovers.

Assumption 3. Knowledge accumulation generates spillovers to the resource and backstop sector. Spillovers to the backstop sector are *strong*: $\phi_H = \phi$, and spillovers to the natural resource are *weak*: $\phi_R < \phi$.

The results of the model depend on this assumption. Nevertheless, the assumption is in accordance with the analysis in Chapter 6, where a model with directed technical change is used to show that the economy converges to a regime in which $\phi_R = 0$.

5.2.6 Factor Markets

Equilibrium on the labor market requires that aggregate labor demand from the intermediate goods sector, the backstop technology sector, and the research sector equals the fixed labor supply of L:

$$L_K + L_H + L_R = K + \frac{H}{\eta} + ag = L. \tag{5.20}$$

Resource extraction depletes the resource stock S according to:

$$\dot{S}(t) = -R(t), \quad S(0) = S_0, \quad R(t) \geqslant 0, \quad S(t) \geqslant 0, \tag{5.21}$$

which implies that total extraction cannot exceed the initial resource stock.

5.2.7 Households

The representative household dynasty lives forever, derives utility from consumption of the final good according to a logarithmic specification, and inelastically supplies L units of labor at each time. It owns the resource stock with value $p_R S$

and it is the owner of all equity in intermediate goods firms with value $p_N N$. The household maximizes lifetime utility[7]

$$U(t) = \int_t^\infty \ln Y(z) e^{-\rho(z-t)} dz, \tag{5.22}$$

subject to the flow budget constraint[8]

$$\dot{V} = r(V - p_R S) + \dot{p}_R S + wL - p_Y Y, \tag{5.23}$$

and a transversality condition:

$$\lim_{z \to \infty} \lambda(z) V(z) e^{-\rho z} = 0, \tag{5.24}$$

where ρ denotes the pure rate of time preference, $V \equiv p_N N + p_R S$ total wealth, and λ the shadow price of wealth. The optimization problem of the representative household gives rise to the familiar rules

$$\hat{Y} = r - \hat{p}_Y - \rho, \tag{5.25}$$

$$\hat{p}_R = r. \tag{5.26}$$

The first one, (5.25), is the Ramsey rule, which requires the growth rate of consumption to equal the difference between the real interest rate and the pure rate of time preference. Equation (5.26) is the Hotelling rule, which ensures that owners of the resource stock are indifferent between selling an additional unit of the resource to earn interest at rate r and conserving it to earn a capital gain at rate $\hat{p}_R$. Although there is no physical capital in the model, the real interest rate is still determined on the market for savings (and investment). The supply of savings is governed by the Ramsey rule (5.25), which can be interpreted as the rate of interest that consumers require for a given rate of consumption growth. The demand for savings $wL_R = wag$ results from (5.18) that links the equilibrium innovation rate to the rate of interest.

5.3 Solving the Model

This section describes the procedure that we perform to solve the model. We will first condense the model to a four-dimensional dynamic system. Subsequently, we

[7]Note that final output cannot be stored and there is no physical capital accumulation in the model, so that consumption equals output, i.e. $C = Y$. Households are still able to intertemporally allocate consumption possibilities by choosing resource extraction and investment in R&D firms.

[8]Appendix 5.A.2 derives the flow budget constraint of the households.

determine its steady state. In the next section, we derive isoclines for the three state variables and perform a numerical analysis to determine the saddle path along which the economy converges to its steady state.

5.3.1 Deriving the Dynamic System

The model described in Section 5.2 constitutes a dynamic system with two predetermined (state) variables: N and S. Moreover, compared to the dynamic system in Chapter 4, the current system features an additional relative price (p_H/p_R). Therefore, the analysis and the visualization of the dynamics of the dynamic system are even more complex. However, we are able to condense the model to a four-dimensional block-recursive system of differential equations in the energy income share θ, the backstop expenditure share ω, the innovation rate g, and the reserve-to-extraction rate $y \equiv S/R$. Beyond simplifying the mathematical analysis, this re-expression of the model also helps to clarify the economics behind our results. The variables of the dynamic system, namely, have a clear interpretation as they are indicators of energy scarcity, fossil fuel addiction, technical progress, and physical resource scarcity. The income and expenditure shares are defined as follows:

$$\theta \equiv \frac{p_E E}{p_Y Y} \Rightarrow 1 - \theta = \frac{p_K K}{p_Y Y}, \tag{5.27a}$$

$$\omega \equiv \frac{p_H H}{p_E E} \Rightarrow 1 - \omega = \frac{p_R R}{p_E E}. \tag{5.27b}$$

The system is block-recursive in the sense that the system of θ, ω, and g can be solved independently from y. All growth rates in the model can be expressed in terms of θ, ω, and g. Subsequently, the differential equation for y can be used to solve for the initial reserve-to-extraction rate, which pins down the initial levels of all variables in the model. In this section, we analyze the dynamic (θ, ω, g)-subsystem described in Proposition 5.1, and we relegate the solution to the differential equation for y to Appendix (5.A.6).

Proposition 5.1. *The dynamics of the model are described by the following three-dimensional system of first-order nonlinear autonomous differential equations in* *the variables* $\theta(t)$*,* $\omega(t)$*, and* $g(t)$*:*

$$\dot{\theta}(t) = \theta(t)[1-\theta(t)][1-\omega(t)](1-\sigma)[r(t)-\hat{w}(t)+\nu g(t)], \tag{5.28}$$

$$\dot{\omega}(t) = \omega(t)[1-\omega(t)](\gamma-1)[r(t)-\hat{w}(t)+\nu g(t)], \tag{5.29}$$

$$\dot{g}(t) = \left(\frac{L}{a}-g(t)\right)\left[\rho-\Gamma_1(t)g(t)-\Gamma_2(t)(r(t)-\hat{w}(t))\right], \tag{5.30}$$

with

$$\Gamma_1 \equiv \nu\theta(1-\omega)[(1-\sigma)(1-\theta)(\omega-\beta)\lambda^{-1}-\omega(1-\gamma)],$$
$$\Gamma_2 \equiv \theta(1-\theta)(1-\omega)(1-\sigma)(\omega-\beta)\lambda^{-1}+[1-\omega(1-\omega)\theta(1-\gamma)],$$
$$\lambda \equiv \beta(1-\theta)+\omega\theta > 0,$$
$$\nu \equiv \phi-\phi_R > 0,$$

where, at an interior solution, the term $r(t)-\hat{w}(t)$ *is a function of* $\theta(t)$*,* $\omega(t)$*, and* $g(t)$*:*

$$r(t)-\hat{w}(t) = \frac{1}{\lambda(t)}\left[(1-\beta)(1-\theta(t))\frac{L}{a}-\{[1-\theta(t)]+\omega(t)\theta(t)\}g(t)\right]. \tag{5.32}$$

Proof. See Appendix 5.A.3. □

5.3.2 Steady State

A steady state of the model is defined as a combination of θ, ω, and g such that $\dot{\theta} = \dot{\omega} = \dot{g} = 0$. The only attainable internal steady state of the system in Proposition 5.1 that satisfies transversality condition (5.24) is given by:[9]

$$g^* = (1-\beta)(1-\theta^*)\left(\frac{L}{a}+\rho\right)-\rho, \tag{5.33a}$$

$$\omega^* = 1. \tag{5.33b}$$

Hence, in line with intuition, the steady state innovation rate depends positively on the maximum attainable innovation rate L/a and the price mark-up in the intermediate goods sector $1/\beta$, and negatively on the rate of time preference ρ. The steady state value of the innovation rate also depends on the income share of energy in the steady state, θ^*. We have to determine this income share separately.

[9] Appendix 5.A.4 discusses the other 4 steady states of the model and shows why they cannot be equilibria.

In the steady state with $\omega = 1$, the resource will not be used anymore so that $R = 0$ and the energy generation function (5.5) boils down to

$$E = \bar{\omega}^{\frac{\gamma}{\gamma-1}} A_H H. \tag{5.34}$$

Substituting (5.34) into (5.4) and using (5.9), (5.12), (5.19), and (5.27), we obtain the steady state income share of energy:

$$\theta^* = \left[1 + \left(\frac{1-\bar{\theta}}{\bar{\theta}} \right)^{\sigma} \left(\bar{\omega}^{\frac{\gamma}{1-\gamma}} \frac{\beta}{\eta} \right)^{\sigma-1} \right]^{-1}. \tag{5.35}$$

The steady state energy income share thus depends negatively on the backstop technology's productivity parameter ω, and positively on β/η, which is the price of a unit of energy generated with the backstop technology relative to the price of intermediate goods.

5.4 Transitional Dynamics

In order to visualize the transition of the economy to the steady state, in this section we derive isoclines for each of the variables θ, ω, and g, along which these variables are constant over time. Subsequently, we calibrate the model, develop a graphical apparatus to visualize the transitional dynamics of the model and numerically solve for the saddle path along which the economy converges to the steady state by using the relaxation algorithm put forward by Trimborn, Koch, and Steger (2008).

5.4.1 Isoclines

Imposing $\dot{\theta} = 0$ in (5.28) and $\dot{\omega} = 0$ in (5.29), we find that the isoclines for θ and ω coincide:

$$g|_{\dot{\theta}=0} = g|_{\dot{\omega}=0} = \frac{\frac{L}{a}\beta(1-\beta)(1-\theta)}{\beta^2(1+\phi_R)(1-\theta) - [1-\beta(2+\phi_R)]\theta\omega}. \tag{5.36}$$

Appendix 5.A.5 discusses the properties of these isoclines. The innovation isocline is obtained by imposing $\dot{g} = 0$ in (5.30), yielding:

$$g|_{\dot{g}=0} = \frac{\frac{L}{a}(1-\beta)(1-\theta)\Lambda_1 - \lambda^2\rho}{[(1-\theta)+\omega\theta]\Lambda_1 + \Lambda_2}, \tag{5.37}$$

where we have defined:

$$\Lambda_1 \equiv \theta(1-\theta)(1-\sigma)(\omega-\beta)(1-\omega) + \lambda[1-(1-\gamma)\theta(1-\omega)\omega],$$
$$\Lambda_2 \equiv [1-\beta(1+\phi_R)]\theta(1-\omega)\lambda\left\{(1-\theta)(1-\sigma)(\beta-\omega)+(1-\gamma)\omega\lambda\right\}\beta^{-1}.$$

Because (5.37) is a complex function of θ and ω, it is cumbersome to construct a phase portrait of the dynamic system for the general case. Therefore, we first calibrate the model and then develop a graphical apparatus to visualize the transitional dynamics for the calibrated model.

5.4.2 Calibration

Empirical evidence suggests that the elasticity of substitution between energy and man-made factors of production is less than unity. Koetse, de Groot, and Florax (2008) conduct a meta-analysis and find a point estimate for the cross-price elasticity between capital and energy in Europe of 0.338 in the short run and 0.475 in the long run. We take the average of these values to obtain $\sigma = 0.4$. According to the estimation results of Roeger (1995), the markup of prices over marginal cost in the manufacturing sector of the U.S. economy over the period 1953-1984 varied from 1.15 to 3.14. We impose $\beta = 0.8$, which is at the top of the range implied by the estimates for the markup.[10] We set the production function parameters $\bar{\theta}$, $\bar{\omega}$, and the rate of pure time preference ρ to 0.1, 0.9, and 0.01, respectively. By imposing $\phi_R = 0.05$, we ensure that knowledge spillovers to the resource extraction sector are small. Labor supply L and the initial knowledge stock $N(0)$ are normalized to 1 and 0.1, respectively. In our benchmark calibration, we assume that the non-renewable resource and the backstop technology are good substitutes, by imposing $\gamma = 50$. We will also study scenarios with lower elasticities of substitution.

The initial resource stock is chosen to get an initial share of resource expenditures in GDP $\theta(0)$ of 8.8 percent, to match the average US energy expenditure share in GDP over the period 1970-2009 U.S. Energy Information Administration

[10] The results for a value of β at the bottom of the implied range are available from the author upon request.

(2011).[11] We use the research productivity parameter a to obtain an initial consumption growth rate $\hat{C}(0)$ of 1.7 percent, which is equal to the average yearly growth rate of GDP per capita in the US over the period 1970-2010 The Conference Board (2011). By setting the backstop production parameter η equal to 3.35, the implied initial ratio between the per unit of energy price of the backstop technology and the resource amounts to 3.[12] According to U.S. Energy Information Administration (2012), the reserve-to-production ratios for oil, natural gas, and coal in 2008 were 44, 58, and 127, respectively. Our implied initial reserve to extraction rate of 50 lies within this range.[13]

5.4.3 Graphical Apparatus

The dynamic system described in Section 5.3.1 is three dimensional. Drawing and analyzing a three-dimensional phase portrait, however, is complex. To simplify the analysis, we therefore show the dynamics of the model in two-dimensional (θ, g)-space while fixing ω at three different values, namely at its minimum ($\omega = 0$), medium ($\omega = \frac{1}{2}$), and maximum ($\omega = 1$) value. Because the locations of the isoclines (5.36)-(5.37) depend on ω, we obtain figures with three different isoclines for the energy income share θ and three different isoclines for the innovation rate g.

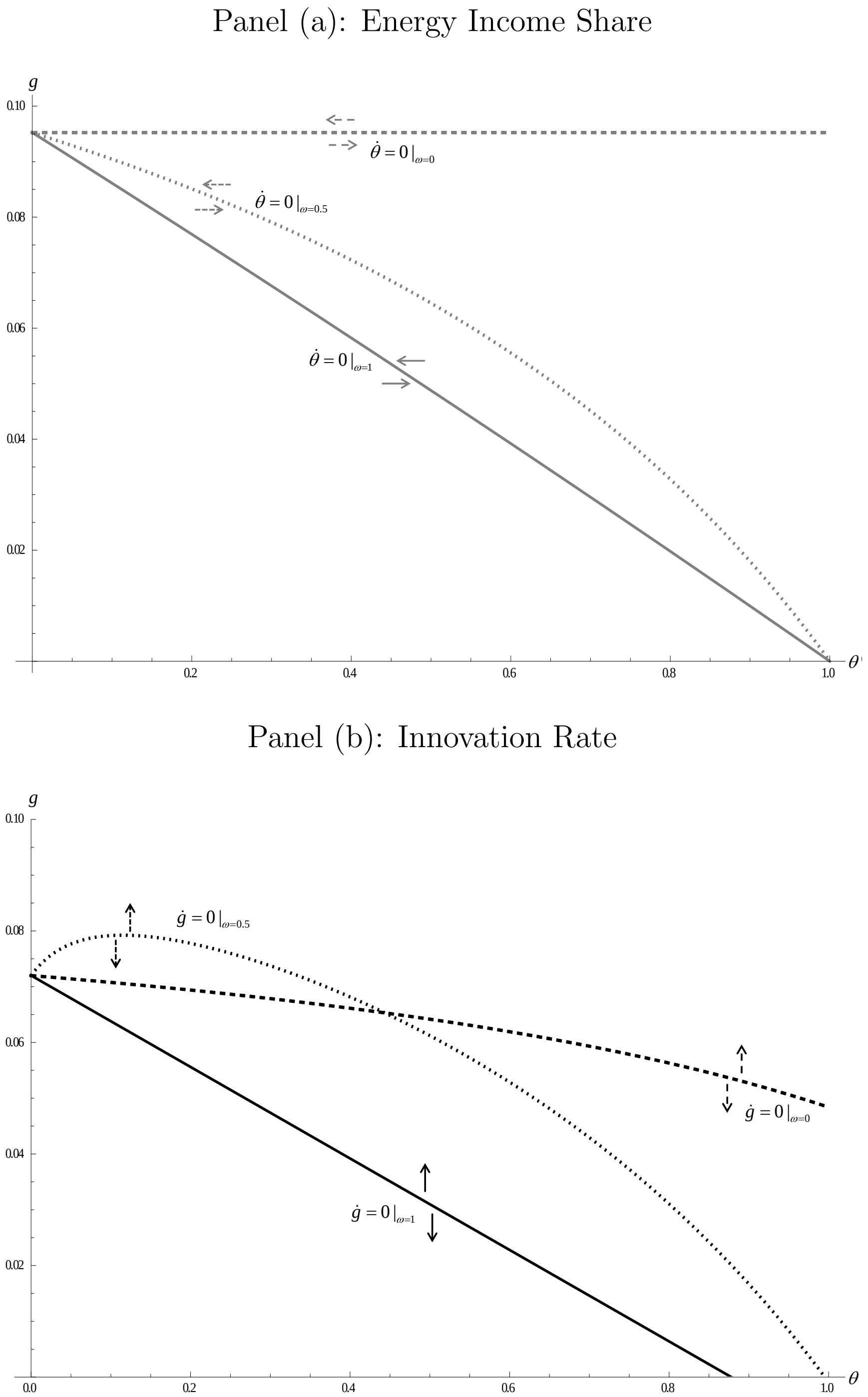
Figure 5.2 shows the income share and innovation isoclines in the (θ, g)-plane. The dashed, dotted, and solid lines correspond to $\omega = 0$, $\omega = 0.5$, and $\omega = 1$, respectively. Panel (a) depicts the income share isoclines and Panel (b) shows the innovation isoclines for the calibrated model. The horizontal arrows in Panel (a) correspond to the direction of the income share development over time and the vertical arrows in Panel (b) indicate the direction of change of the innovation rate. If the backstop technology is not used at all, i.e. when $\omega = 0$, the isoclines in Figure 5.2, which are depicted by the dashed lines, coincide with the ones that were obtained in the resource regime in Chapter 4, where the resource and the backstop technology are perfect substitutes. At the other extreme, if only the backstop technology is used for energy generation, the isoclines are depicted by

[11] We attribute energy expenditure entirely to resource expenditure, although part of the energy expenditure in the data consists of factor costs. Taking this distinction into account would imply a smaller initial resource expenditure share, without affecting the dynamics of the model.

[12] Using (A.5.14), this ratio is given by $[\omega(0)/(1-\omega(0))]^{\frac{1}{1-\gamma}}$.

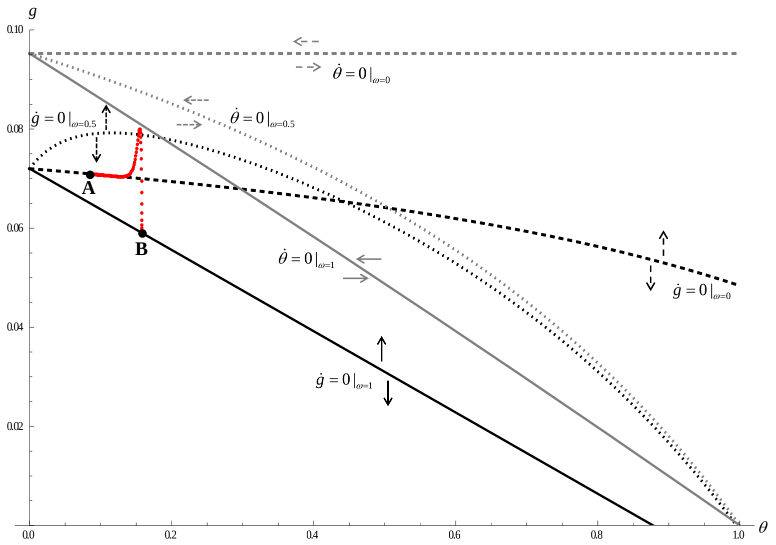
[13] The initial expenditure on quality improvement as a share of GDP is equal to 15 percent. Given that expenditure on innovation is the only investment possibility in the model, this number should be interpreted as the aggregate investment share in the economy.

Figure 5.2: Income share and innovation rate isoclines



Notes: The dashed lines correspond to the isoclines for $\omega = 0$, the dotted lines to the isoclines for $\omega = 0.5$, and the solid lines to the isoclines with $\omega = 1$. In Panel (a), the horizontal arrows indicate the direction of the income share dynamics for each isoline. In Panel (b), the vertical arrows indicate the direction of the innovation rate dynamics for each isocline.

Figure 5.3: Transitional Dynamics



Notes: The gray and black lines are the isoclines for the income share and the innovation rate, respectively. The dashed lines correspond to the isoclines for $\omega = 0$, the dotted lines to the isoclines for $\omega = 0.5$, and the solid lines to the isoclines with $\omega = 1$. The horizontal arrows indicate the direction of the income share dynamics for each income share isoline that is depicted. The vertical arrows indicate the direction of the innovation rate dynamics for each innovation rate isocline that is depicted. The fat dots represent the saddle path leading to the steady state at point B.

the solid lines in the figure and the innovation isoline coincides with the one that is obtained in the backstop regime of Chapter 4. The income share isocline in Panel (a) is linear at these two extremes (flat at $\omega = 0$ and downward-sloping at $\omega = 1$), but concave and downward-sloping for the intermediate case with $\omega = 0.5$. The innovation isocline in Panel (b) is linear and downward-sloping at the backstop extreme with $\omega = 1$. It is concave and downward sloping for the other cases. Its intersection with the vertical line $\theta = 1$ is decreasing in the value of ω, but the vertical intercept is independent of ω.

Figure 5.3 shows both isoclines (again for three different values of ω) and the saddle path along which the economy converges from point A to the steady state, which is indicated with point B.[14] The saddle path is located below all depicted income share isoclines, implying that the income share of energy is increasing over time. From (A.5.13) and (A.5.15) it is clear that sgn $\dot{\omega}$ = sgn $\dot{\theta}$, so that the backstop expenditure share is increasing over time during the transition to

[14]The start point of the saddle path, point A in Figure 5.3, is determined by imposing that total resource extraction equals the initial resource stock, as shown in Appendix 5.A.6.

the steady state. The first part of the saddle path is located below the relevant innovation isocline, so that the innovation rate is initially decreasing over time. However, after the saddle path has crossed the innovation isocline, the innovation rate starts to increase over time. During the convergence to the steady state, the backstop expenditure share increases, so that the innovation isocline initially becomes more concave (see the difference between the black dashed and the black dotted lines). Hence, during the phase of increasing extraction, both the actual innovation rate that moves along the saddle path and the value of the innovation rate attached by the innovation isocline to the current actual income share of energy, move upwards. As soon as the isocline passes the point on the saddle path at which the economy is located, the innovation rate starts to decline again and converges to point B at the innovation isocline corresponding to $\omega = 1$. Therefore, whereas during the transition, when $0 < \omega < 1$, both the resource and the backstop technology are used, over time ω increases and in the long run the economy will converge to a regime with $\omega = 1$ in which only the backstop technology will be used for energy generation. We will interpret the dynamic behavior of the energy income share, the backstop technology expenditure share, and the innovation rate in the next section.

5.5 Results

This section discusses our simulation results. We determine the time paths of the innovation rate, resource extraction, energy generation with the backstop technology, and the growth rate of consumption numerically. Our focus will be on the effect of the ease with which the backstop technology is able to replace the non-renewable resource. Therefore, we simulate the model for various levels of the elasticity of substitution between the two energy sources. Moreover, we compare our results to those of Chapter 4, in which the extreme cases of perfect and no substitution between the resource and the backstop technology is analyzed.

Figure 5.4 shows the time profiles of g, R, H, and $\hat{C}$ for different scenarios: perfect, good, intermediate, moderate, and no substitution possibilities. The solid black lines represent the outcomes of the first scenario, where the resource and the backstop technologies are good substitutes ($\gamma = 50$). The dotted line represents the intermediate substitution scenario ($\gamma = 10$) and the dashed black line gives the time path for the moderate substitution scenario ($\gamma = 5$). The gray lines depict the extreme cases: the solid gray lines correspond to the scenario in which the backstop and the resource are perfect substitutes and the dotted gray lines represent the time paths in economies without a backstop technology.[15]

Panel (a) of Figure 5.4 gives the time profiles of the innovation rate.[16] In the good substitutes scenario (see the solid black line), though less pronounced, we obtain the same non-monotonicity as in the model with perfect substitution. The reason is that the same mechanism is at work. During the run-up to the backstop technology in the perfect substitutes model, the innovation rate increases to prevent a downward jump in consumption at the moment that the economy switches completely to the backstop technology: the innovation rate necessarily jumps down to free labor as soon as energy generation with the backstop technology jumps up. In our imperfect substitutes model, the change to the backstop technology occurs less abrupt, but households still want to smooth consumption over time. As a result, by increasing savings (and thus innovation) before generating energy with the backstop technology will absorb a substantial part of the economy's productive capacity, households effectively transfer part of their resource wealth to the backstop era during which energy generation comes at cost of production.

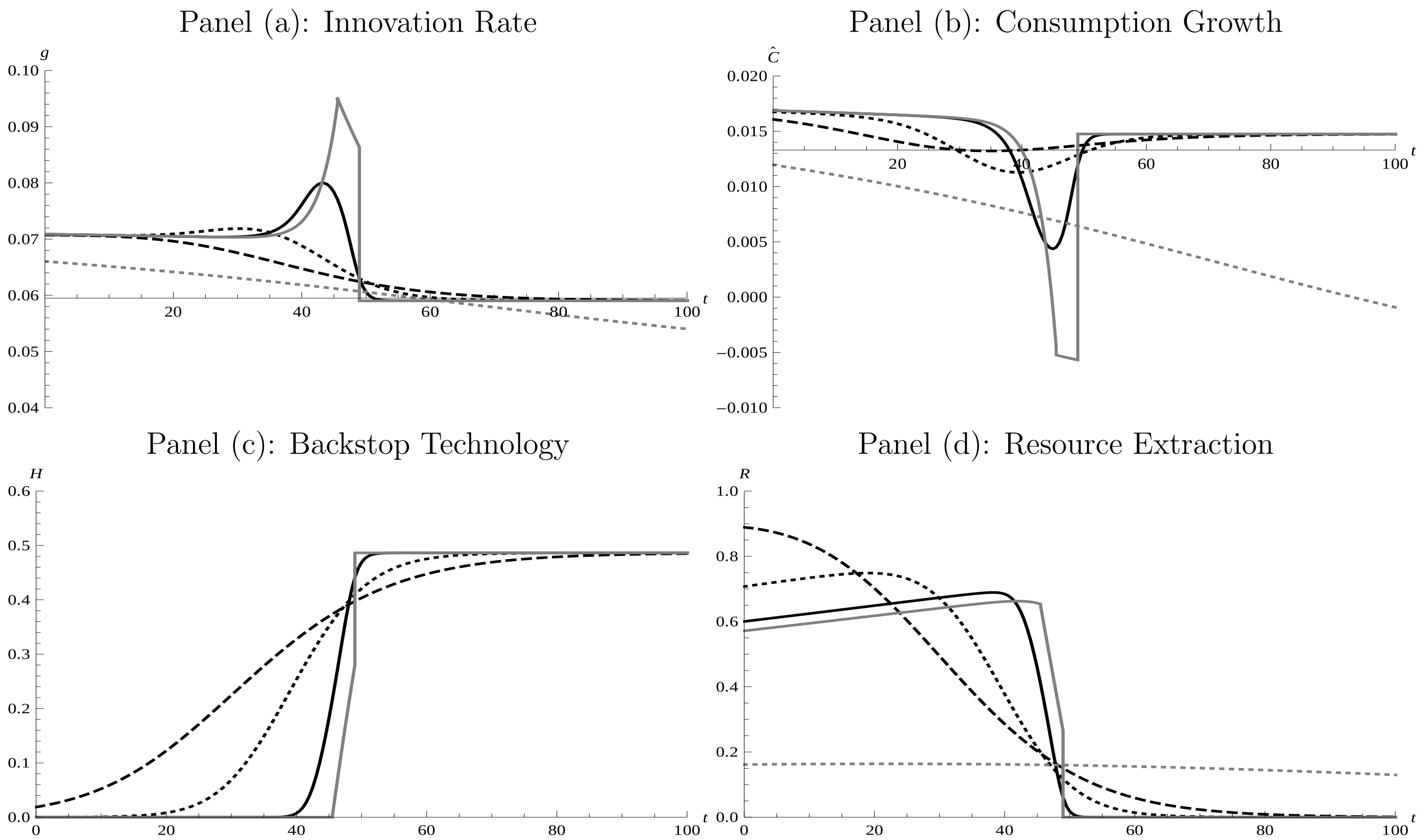
For lower levels of the elasticity of substitution, the transition to the backstop technology occurs more gradually. As a result, the non-monotonicity in the time profile of the innovation rate becomes weaker in the intermediate scenario and even disappears completely in the scenario with only moderate substitution possibilities (see the dotted and dashed black lines). Intuitively, if the generation of energy with the backstop is not going to increase from almost zero to its positive long-run value very quickly, there is no need to smooth consumption over time by increasing investment considerably to compensate for the fall in output just after the quick introduction of the backstop technology.

It is clear from Panel (a) that the good substitutes scenario is close to the perfect substitutes case. The intermediate and moderate substitutes scenarios differ considerably from the perfect substitutes case during the transition to the backstop technology. In the short and long run, however, all scenarios with an elasticity of substitution exceeding unity lead to identical innovation rates, in line

[15] The current model nests the model of Chapter 4: by taking the limits $\gamma \to \infty$ and $\bar{\omega} \to 0$, we obtain the specification with perfect and no substitutes, respectively.

[16] Note that this is not innovation in the backstop technology, but in intermediate goods. A reasoning that the pattern in Panel (a) of Figure 5.4 can be explained by the fact that investment in clean energy should be concentrated around the time of implementation of the backstop technology therefore does not apply.

Figure 5.4: Transitional Dynamics with Varying Substitution Possibilities



Notes: The five different lines represent cases with a different substitution elasticity between the backstop technology and the non-renewable resource. The solid black line represents the scenario with $\gamma = 50$, the dotted black line represents the scenario with $\gamma = 10$, the dashed black line represents the scenario with $\gamma = 5$, the solid gray line represents the scenario with $\gamma \to \infty$, and the dotted gray line represents the scenario with $\gamma = 0$. The underlying parameter values are: $a = 2.5$, $\beta = 0.8$, $\phi_R = 0.05$, $\eta = 0.215$, $\rho = 0.01$, $\sigma = 0.4$, $\bar{\theta} = 0.9$, $\bar{\omega} = 0.9$, $L = 1$. The backstop productivity parameter η equals 3.35 in scenario 1. In the other scenarios, η is adjusted to obtain the same θ^* as in scenario 1. The initial knowledge stock N_0 equals 0.1. The initial resource stock S_0 equals 275 to obtain $\theta_0 = 0.912$ in scenario 1.

with the observation that the non-monotonicity in the time profile is a transitional result of consumption smoothing between the resource and the backstop era. The model without a backstop technology (see the dotted gray line) generates a monotonically declining innovation rate that starts below the innovation rates in the scenarios with a backstop technology.

Panel (b) shows a similar record for the growth rate of consumption. Consumption growth declines substantially just before the introduction of the backstop technology in the perfect and good substitution scenarios. The reason is the increase in innovation during the run-up to the backstop technology, which comes at cost of consumption possibilities. The non-monotonicity in the time profile becomes weaker for smaller values of the elasticity of substitution between the backstop technology and the resource. In the long run, consumption growth is the same in all scenarios in which there exists a backstop technology.

The time profiles of energy generation with the backstop technology in Panel (c) confirm that the switch from the resource to the backstop technology occurs more gradually if substitution possibilities between the two energy sources are limited. In the good and perfect substitutes scenario, there is a clear distinction between a resource era where the backstop technology is not used (or only to a very small extent) and a backstop era where the resource is effectively not used anymore. This clear distinction disappears when the elasticity of substitution between the backstop technology and the resource becomes smaller, as this results in a prolonged period of simultaneous use of both energy sources.

Panel (d) shows that the time profile of resource extraction may be increasing temporarily. This is a consequence of the imperfect substitutability between energy and intermediate goods. To see this, we decompose the income share of the resource into the income share of energy and the fossil fuel share in total energy expenditures:

$$\frac{p_R R}{p_Y Y} = (1-\omega)\theta \Rightarrow \hat{R} = -\frac{\omega}{1-\omega}\hat{\omega} + \hat{\theta} - \rho, \tag{5.39}$$

where the second equality uses the rules of Ramsey and Hotelling (5.25)-(5.26). Hence, if the energy income share θ increases fast enough, and the backstop expenditure share ω increases not too fast, resource extraction grows over time.

Panel (d) furthermore reveals that, in line with the literature on the Green Paradox, the availability of a backstop technology leads to front-loading of resource extraction. At the same time, however, we also find a 'Weak Green Orthodox':

an invention that makes the backstop technology a closer substitute to the non-renewable resource leads to an immediate decrease in resource extraction. The reason is that an increase in the elasticity of substitution between the backstop technology and the resource lowers the initial use of the backstop technology and postpones the moment at which the usage of the backstop technology grows beyond a negligible amount.[17] As a result, there will be a longer period during which energy generation relies heavily on the resource, so that initial extraction must go down. In the long run, the outcomes are the same in the four scenarios with a backstop technology available: the economy will asymptotically approach a regime in which only the backstop technology will be used for energy generation. To obtain this long-run neutrality of the elasticity of substitution between the resource and the backstop technology, we endogenously vary the backstop productivity parameter η so that the long-run energy income share is the same in each scenario, see (5.35).[18]

Summarizing the results and linking them to the different features of the model, we first find a non-monotonicity of innovation and consumption growth for high values of the elasticity of substitution, due to consumption smoothing of the households. Second, the model generates simultaneous use of the resource and the backstop technology, because those two inputs are imperfect substitutes. Third, the time path of resource extraction can be temporarily upward sloping, because energy and intermediate goods are gross complements. Fourth, the introduction of the backstop technology leads to a Weak Green Paradox, because of the Hotelling rent on the non-renewable resource. Finally, an increase in the substitutability between energy inputs gives rise to a Weak Green Orthodox, because of the gross complementarity of intermediate goods and energy, the effect on the initial importance of the backstop technology and therefore on the subsequent increase in its use, and the effect of changes in future energy demand due to output growth.

5.6 Conclusion

We have investigated the effect of different degrees of substitutability on the transition from a non-renewable resource to a backstop technology. For this purpose, we

[17] Recall the extreme situation of no backstop use until the regime shift in the case of perfect substitutes that Chapter 4 describes.

[18] When keeping η constant, the long-run effects will differ only marginally between the scenarios. The qualitative results of the model remain unchanged.

have constructed a general equilibrium endogenous growth model in which growth is driven by R&D and energy can be generated by a non-renewable resource and a backstop technology. The resource and the backstop technology are good, but imperfect substitutes for each other. We take into account that energy generation with the backstop technology is costly and that energy and man-made factors are poor substitutes. The steady state equilibrium is determined analytically. We calibrate and simulate the model to visualize its transitional dynamics.

Contrary to Chapter 4 and a large part of the scientific literature that simplifies the analysis by assuming perfect substitution, we do not find different regimes of energy generation. The economy gradually shifts from mainly using the non-renewable resource to mainly using the backstop technology for energy generation. In other words, we find a prolonged period of simultaneous use of both energy sources. The lower the elasticity of substitution between the resource and the backstop technology, the longer is the period during which a non-negligible amount of both energy sources is used simultaneously.

If the elasticity of substitution between the inputs in energy generation is large enough, our results come close to those obtained in models with perfect substitution that are otherwise similar. In particular, we find a strong increase in investment during the transition to the backstop technology, similar to what happens in Chapter 4. This result disappears if substitution possibilities are more modest. The availability of a backstop technology results in front-loading of resource extraction, in line with the literature on the Green Paradox. At the same time, however, we also find a Weak Green Orthodox: an invention that increases the substitutability between the backstop technology and the non-renewable resource leads to a short-run decrease in resource extraction. Although the transition to the backstop technology thus crucially depends on the ease with which the resource can be replaced by the backstop technology, the long-run outcomes of the model are not affected by the substitution possibilities in the energy sector as long as the elasticity of substitution exceeds unity.

Because of its effect on resource extraction, the value of the elasticity of substitution in the energy sector is relevant for the strength of the Weak Green Paradox. However, to address the role of imperfect substitution for the Strong Green Paradox, the model needs to be extended with stock-dependent extraction costs and feedback effects of pollution from resource combustion on either production or utility so that the discounted value of environmental damages can be calculated. Another direction for future research would be to endogenize the direction of technical change, in order to investigate the interaction between the backstop technology and the direction and pace of technological progress. This will be the topic of the next chapter.

5.A Appendix

This Appendix contains the derivations of the mathematical results in the main text of the chapter.

5.A.1 Energy Price Index

The first-order conditions for the allocation of expenditure between the resource R and the backstop H in the energy sector are given by:

$$\frac{\partial E}{\partial R} = \left[\bar{\omega}(A_H H)^{\frac{\gamma-1}{\gamma}} + (1-\bar{\omega})(A_R R)^{\frac{\gamma-1}{\gamma}}\right]^{\frac{1}{\gamma-1}} \bar{\omega}(A_H H)^{-\frac{1}{\gamma}} A_H = p_H, \quad \text{(A.5.1)}$$

$$\frac{\partial E}{\partial R} = \left[\bar{\omega}(A_H H)^{\frac{\gamma-1}{\gamma}} + (1-\bar{\omega})(A_R R)^{\frac{\gamma-1}{\gamma}}\right]^{\frac{1}{\gamma-1}} (1-\bar{\omega})(A_R R)^{-\frac{1}{\gamma}} A_R = p_R. \quad \text{(A.5.2)}$$

By combining (A.5.1), (A.5.2), the first row of (5.5), and $p_E E = p_H H + p_R R$, we obtain an expression for the energy price index:

$$p_E = [\bar{\omega}(1-\bar{\omega})]^{-1} \left\{ \bar{\omega} \left[(1-\bar{\omega}) \frac{p_H}{A_H} \right]^{1-\gamma} + (1-\bar{\omega}) \left[\omega \frac{p_R}{A_R} \right]^{1-\gamma} \right\}^{\frac{1}{1-\gamma}}. \quad \text{(A.5.3)}$$

Converting (A.5.3) into growth rates, we get:

$$\hat{p}_E = \bar{\omega}^{\gamma} \left(\frac{p_H}{A_H p_E} \right)^{-\gamma} (\hat{p_H} - \hat{A_H}) + (1-\bar{\omega})^{\gamma} \left(\frac{p_R}{A_R p_E} \right)^{1-\gamma} (1-\omega)(\hat{p}_R - \hat{A}_R). \text{(A.5.4)}$$

By using (5.7) into the first row of (5.5), we can rewrite (A.5.4) to obtain (A.5.12).

5.A.2 Flow Budget Constraint

In this section we derive the flow budget constraint of the households (5.23). Total wealth is equal to $V = p_N N + p_R S$, so that the change in wealth is given by

$$\dot{V} = \dot{p}_N N + p_N \dot{N} + \dot{p}_R S + p_R \dot{S} = \dot{p}_N N + p_N \dot{N} + \dot{p}_R S - p_R R, \quad \text{(A.5.5)}$$

where the second equality uses (5.21). Nominal GDP can be written as

$$\begin{aligned} p_Y Y &= p_K K + p_R R + p_H H = \pi N + w L_K + p_R R + p_H H \\ &= r p_N N - \dot{p}_N N + w L_K + p_R R + p_H H, \end{aligned} \quad \text{(A.5.6)}$$

where the second and third equality use (5.10) and (5.17), respectively. Using (A.5.6) to substitute for $p_R R$ in (A.5.5), we obtain:

$$\dot{V} = p_N \dot{N} + \dot{p}_R S - p_Y Y + r p_N N + w L_K + p_H H = r p_N N + \dot{p}_R S + w L - p_Y Y, \tag{A.5.7}$$

where we have used (5.11), (5.12), (5.15), and (5.20) for the second equality. Using the definition of wealth again, we get (5.23).

5.A.3 Dynamic System

In this section, we will derive the differential equations for θ, ω, and g. Because each of them will feature the rate of return to innovation, we start by rewriting (5.18) in terms of these three variables. Using the definitions in (5.27), we express the output of the substitute as follows

$$H = \frac{\omega\theta}{1-\theta}\frac{p_K}{p_H} = \frac{\omega\theta}{1-\theta}\frac{\eta}{\beta}, \tag{A.5.8}$$

where the second equality uses the pricing equations (5.9) and (5.12). Substitution of (A.5.8) into the labor market equilibrium (5.20) yields:

$$K = \frac{(1-\theta)\beta}{\omega\theta + (1-\theta)\beta}(L - ag). \tag{A.5.9}$$

We use this expression to substitute for K in (5.18), so that the return to innovation becomes

$$r - \hat{w} \geqslant \frac{1}{\omega\theta + (1-\theta)\beta}\left[(1-\beta)(1-\theta)\frac{L}{a} - [(1-\theta) + \omega\theta]g\right], \tag{A.5.10}$$

with equality if $g > 0$. When we substitute definition (5.27) into (5.4), the relative factor income share and its growth rate can be written as

$$\frac{\theta}{1-\theta} = \left(\frac{\bar{\theta}}{1-\bar{\theta}}\right)^{\sigma} N^{\phi(1-\sigma)}\left(\frac{p_E}{p_K}\right)^{1-\sigma} \Rightarrow \hat{\theta} = (1-\theta)(1-\sigma)[\hat{p}_E - (\hat{p}_K - \phi g)], \tag{A.5.11}$$

Consequently, the income share of energy increases if the effective relative price of energy and intermediates increases (the relative productivity change is captured by the term ϕg), because we have assumed that $\sigma < 1$ implying that energy an intermediates are bad substitutes. In Appendix 5.A.1 we show that energy price changes according to

$$\hat{p}_E = \omega(\hat{p}_H - \phi_H g) + (1-\omega)(\hat{p}_R - \phi_R g). \tag{A.5.12}$$

Substitution of (A.5.12) into the final result of (A.5.11), we obtain differential equation (5.28) in the main text, which governs the evolution of the income share of energy:

$$\begin{aligned}\dot{\theta} &= \theta(1-\theta)(1-\sigma)(1-\omega)[\hat{p}_R - \phi_R g - (\hat{p}_K - \phi g)] \\ &= \theta(1-\theta)(1-\sigma)(1-\omega)[r - \hat{w} + \nu g],\end{aligned} \tag{A.5.13}$$

where ν measures the bias in technical change and we have used the pricing equations (5.9), (5.12) and the Hotelling rule (5.26). This expression reveals that the income share of energy goes up if the effective relative price of the resource and intermediates increases.

By using (5.19) and definition (5.27) in the relative factor demand function (5.7), we get the following expression for the expenditure share in the energy sector:

$$\frac{\omega}{1-\omega} = \left(\frac{\bar{\omega}}{1-\bar{\omega}}\right)^{\gamma} N^{\nu(\gamma-1)} \left(\frac{p_R}{p_H}\right)^{\gamma-1}. \tag{A.5.14}$$

Converting (A.5.14) into growth rates and multiplying the result by ω, we obtain differential equation (5.29) in the main text, which describes the evolution of the expenditure share of the backstop technology in the energy sector:

$$\begin{aligned}\dot{\omega} &= \omega(1-\omega)(\gamma-1)[\hat{p}_R - \phi_R g - (\hat{p}_H - \phi g)] \\ &= \omega(1-\omega)(\gamma-1)[r - \hat{w} + \nu g],\end{aligned} \tag{A.5.15}$$

where the second equality uses the pricing equation (5.12) and the Hotelling rule (5.26) again. Equation (A.5.15) shows that the expenditure share on the backstop technology goes up if the relative price of the backstop technology decreases, because $\gamma > 1$, implying that the resource and the backstop technology are good substitutes.

In order to derive the differential equation for the innovation rate g, we first convert the labor market equilibrium condition (A.5.9) into growth rates:

$$\hat{K} = -\frac{1}{\beta(1-\theta)+\theta\omega}\left[\frac{\omega\theta}{1-\theta}\hat{\theta} + \omega\theta\hat{\omega}\right] - \frac{\dot{g}}{\frac{L}{a} - g}. \tag{A.5.16}$$

The income share definition (5.27) implies

$$\hat{\theta} = -\frac{1-\theta}{\theta}\left[\hat{p}_K + \hat{K} - (\hat{p}_Y + \hat{Y})\right] = -\frac{1-\theta}{\theta}\left[\hat{K} + \rho - (r - \hat{w})\right], \tag{A.5.17}$$

where the second equality uses the pricing equation (5.9) and the Ramsey rule (5.25). Substituting of (A.5.10) and (A.5.16) into (A.5.17), we find the differential equation (5.30) in the main text.

5.A.4 Steady States

Proposition 5.2. *The only attainable internal steady state that satisfies the transversality conditions is given by* (5.33). *The other four steady states of the model satisfy:*

$$g^* = \frac{L}{a} > 0, \quad \omega^* = 1 > 0, \tag{A.5.18a}$$

$$g^* = \frac{L}{a} > 0, \quad \theta^* = 0, \quad \omega^* = 0, \tag{A.5.18b}$$

$$g^* = \frac{L}{a}(1-\beta) - \beta\rho, \quad \theta^* = 0, \quad \omega^* = 0, \tag{A.5.18c}$$

$$\begin{aligned} g^* &= -\frac{\beta\rho}{1-\beta(1+\phi_R)} < 0, \\ \theta^* &= \frac{\frac{L}{a}(1-\beta)[1-\beta(1+\phi_R)] + \beta^2(1+\phi_R)\rho}{\frac{L}{a}(1-\beta)[1-\beta(1+\phi_R)] + \rho\left[\beta^2(1+\phi_R) + \omega[1-\beta(2+\phi_R)]\right]}. \end{aligned} \tag{A.5.18d}$$

Proof. The derivation of (5.33) is provided in the text. The first two steady states (A.5.18a) and (A.5.18b) do not satisfy the transversality condition, because substitution of $K^* = L - ag^* = 0$ into (5.18) implies $(r - \hat{w})^* = -g^* < 0$ and the transversality condition (5.24) in growth rates requires:

$$\lim_{t\to\infty} = \hat{p}_N(t) + \hat{N}(t) - r(t) \leqslant 0 \Rightarrow \lim_{t\to\infty} r(t) - \hat{w}(t) \geqslant 0, \tag{A.5.19}$$

where the second equality uses (5.15) and (5.26). Hence, the two steady states with $(r - \hat{w})^* = -g^* < 0$ do not satisfy the transversality condition. Steady state (A.5.18c) is located at the intersection of the innovation locus with the $\theta = 0$ line, and below the income share locus in (θ, g)-space. It is immediately clear from the dynamics in Figure 5.3 ($\dot{\theta} > 0$) that this steady state cannot be attained. The economy can only be situated here if there is an infinite amount of oil available from the beginning (so that $\theta^* = 0$), which is impossible. Steady state (A.5.18d) cannot be an internal equilibrium, because this requires $g > 0$. □

5.A.5 Properties of Differential Equations and Isoclines

The first-order derivative of the income and expenditure share isoclines with respect to θ is given by:

$$\frac{\partial(g|_{\dot{\theta}=0})}{\partial\theta} = \frac{\partial(g|_{\dot{\omega}=0})}{\partial\theta} = -\frac{\frac{L}{a}(1-\beta)\beta\omega[1-\beta(2+\phi_R)]}{[\beta^2(1+\phi_R)(1-\theta)-[1-\beta(2+\phi_R)]\theta\omega]^2}. \quad \text{(A.5.20)}$$

Hence, we have $\beta(2+\phi_R) > 1 \Rightarrow \partial(g|_{\dot{\theta}=0})/\partial\theta < 0$ and the isocline has a vertical asymptote at

$$\theta = 1-\beta^2(1+\phi_R)-\omega[1-(2+\phi_R)\beta] \in (0,1) \quad \text{if} \quad \beta(2+\phi_R) < 1. \quad \text{(A.5.21)}$$

The first-order derivatives of the income and expenditure share differential equations are given by:

$$\frac{\partial\dot{\theta}}{\partial g} = -\frac{\theta(1-\theta)(1-\sigma)(1-\omega)[\beta^2(1+\phi_R)(1-\theta)-[1-\beta(2+\phi_R)]\theta\omega]}{\beta\lambda}, \quad \text{(A.5.22)}$$

$$\frac{\partial\dot{\omega}}{\partial g} = -\frac{(\gamma-1)(1-\omega)\omega[\beta^2(1+\phi_R)(1-\theta)-[1-\beta(2+\phi_R)]\theta\omega]}{\beta\lambda}. \quad \text{(A.5.23)}$$

Hence, sgn $\partial\dot{\theta}/\partial g$ = sgn $\partial\dot{\omega}/\partial g$ and $\beta(2+\phi_R) > 1 \Rightarrow \partial\dot{\theta}/\partial g < 0, \partial\dot{\omega}/\partial g < 0$.

5.A.6 Initial Condition

To determine the initial point $[\theta(0), \omega(0), g(0)]$, we exploit the fact that total resource extraction over time should be equal to the initial resource stock. From the definition (5.27) we have $E = p_R R/[p_E(1-\omega)]$. If we additionally define $y \equiv S/R$ as the reserve-to-extraction rate, and use both definitions in (5.4), we obtain:

$$\frac{\theta}{1-\theta} = \frac{\bar{\theta}}{1-\bar{\theta}}\left(\frac{p_E}{p_R}\frac{(1-\omega)yK}{S}\right)^{\frac{1-\sigma}{\sigma}}. \quad \text{(A.5.24)}$$

Combining (A.5.11), (A.5.14), (5.9), and (5.12), we obtain:

$$\frac{p_E}{p_R} = \frac{\eta}{\beta}\left(\frac{\theta}{1-\theta}\right)^{\frac{1}{1-\sigma}}\left(\frac{\bar{\theta}}{1-\bar{\theta}}\right)^{\frac{\sigma}{\sigma-1}}\left(\frac{\omega}{1-\omega}\right)^{\frac{1}{1-\gamma}}\left(\frac{\bar{\omega}}{1-\bar{\omega}}\right)^{\frac{\gamma}{1-\gamma}} N^{\nu}. \quad \text{(A.5.25)}$$

Substitution of (A.5.25) into (A.5.24), we obtain an expression for y in terms of the system variables θ, ω, g, and the state variables N and S:

$$y = \left(\frac{\omega}{1-\omega}\right)^{\frac{\gamma}{\gamma-1}}\left(\frac{\bar{\omega}}{1-\bar{\omega}}\right)^{\frac{\gamma}{1-\gamma}}\frac{[\theta\omega+(1-\theta)\beta]SN^{-\nu}}{\theta\omega\eta(L-ag)}. \quad \text{(A.5.26)}$$

For given values of $N(0)$ and $S(0)$, (A.5.26) gives a relationship between y and the initial values of θ, ω, g. Converting (A.5.24) into growth rates, and using (5.9), (5.12), (5.26), (5.27), (A.5.12), (A.5.13), (A.5.15), and $\hat{S} = -y^{-1}$, we obtain a differential equation for y:

$$\dot{y} = -\left[(1-\omega)(1-\sigma)(1-\theta) + \omega(1-\gamma)\right](r - \hat{w} + \nu g) + \rho y - 1. \qquad \text{(A.5.27)}$$

Substitution of (A.5.10) into (A.5.27) gives:

$$\begin{aligned} \dot{y} = & -\left[(1-\omega)(1-\sigma)(1-\theta) + \omega(1-\gamma)\right] \\ & \left\{\frac{(1-\beta)(1-\theta)}{\theta\omega + (1-\theta)\beta}\frac{L}{a} + \left(\nu - \frac{(1-\theta)+\omega\theta}{\theta\omega + (1-\theta)\beta}\right)g\right\} y + \rho y - 1. \end{aligned} \qquad \text{(A.5.28)}$$

Imposing $\dot{y} = 0$ in (A.5.28) gives the reserve-to-extraction rate isocline. The equality between total extraction and the initial resource stock, which necessarily follows from (5.21) and the positive marginal product of energy, requires y to converge to this isocline. Because the time paths of θ, ω, and g are already determined, the y-isocline pins down the steady state value of y. The differential equation (A.5.28) can subsequently be used to construct the saddle path of y through (θ, ω, g, y)-space. Because at $t = 0$, y must be located at this saddle path and y must also satisfy (A.5.26), the intersection point of (A.5.26) and the saddle path of y determines the initial point $[\theta(0), \omega(0), g(0), y(0)]$.

5.A.7 Derivative CES-function

In this section, we prove that the derivative of a CES-function with respect to the elasticity of substitution is positive if the effective inputs are not equal to each other. To simplify notation, we define $\alpha \equiv (\gamma-1)/\gamma$ so that $d\alpha/d\gamma = \gamma^{-2} > 0$, and we normalize $A_R = A_H = 1$.

Proposition 5.3. *Let* $E = \left(\bar{\theta}H^{\alpha} + (1-\bar{\theta})R^{\alpha}\right)^{\frac{1}{\alpha}}$, *where* $\bar{\theta} \in (0,1)$ *and* $\alpha \in \{(-\infty, 1)\backslash 0\}$. *This function has the following property:* $\partial E/\partial\alpha > 0 \Leftrightarrow E \neq R$.

Proof. Without loss of generality, we impose $H = \chi R$. The first-order derivative of E with respect to α is then given by:

$$\begin{aligned} \frac{\partial E}{\partial \alpha} &= \frac{E}{\alpha}\left[\frac{(1-\bar{\theta})R^{\alpha}\ln R + \bar{\theta}(\chi R)^{\alpha}\ln(\chi R)}{E^{\alpha}} - \frac{\ln E}{\alpha}\right] \\ &= \frac{E}{\alpha}\left[\ln R - \ln E + \frac{\bar{\theta}}{(1-\bar{\theta}) + \bar{\theta}\chi^{\alpha}}\right]. \end{aligned}$$

Using $E/R = [(1-\bar{\theta}) + \bar{\theta}\chi^{\alpha}]^{\frac{1}{\alpha}}$, taking the logarithm and substituting the result into the derivative, we obtain: $\partial E/\partial\alpha = E/\alpha\,(\Delta_1 + \Delta_2)$, where we have defined

$$\Delta_1 \equiv \frac{\bar{\theta}\chi^{\alpha}}{(1-\bar{\theta}) + \bar{\theta}\chi^{\alpha}} < 0, \tag{A.5.29a}$$

$$\Delta_2 \equiv -\frac{1}{\alpha}\ln\left((1-\bar{\theta}) + \bar{\theta}\chi^{\alpha}\right). \tag{A.5.29b}$$

These Δ's have the following properties: $\Delta_1 \gtreqless 0 \Leftrightarrow \chi \gtreqless 1$ and $\Delta_2 \lesseqgtr 0 \Leftrightarrow \chi \gtreqless 1$. Their first-order derivatives with respect to χ are given by:

$$\frac{\partial\Delta_2}{\partial\chi} = -\frac{\chi^{\alpha-1}\bar{\theta}}{\chi^{\alpha}\bar{\theta} + (1-\bar{\theta})} < 0, \tag{A.5.30a}$$

$$\frac{\partial\Delta_1}{\partial\chi} = -\frac{\partial\Delta_2}{\partial\chi}\left[1 + \left(1 - \frac{\bar{\theta}\chi^{\alpha}}{(1-\bar{\theta}) + \bar{\theta}\chi^{\alpha}}\right)\ln\chi\right] > 0 \quad \text{if} \quad \chi > 1. \tag{A.5.30b}$$

Finally, by defining $\Delta \equiv \Delta_1 + \Delta_2$ we find

$$\chi < 1 \Rightarrow \partial\Delta_1\partial\chi < -\partial\Delta_2/\partial\chi \Rightarrow \partial\Delta/\partial\chi < 0, \tag{A.5.31a}$$

$$\chi > 1 \Rightarrow \partial\Delta_1\partial\chi > -\partial\Delta_2/\partial\chi \Rightarrow \partial\Delta/\partial\chi > 0. \tag{A.5.31b}$$

Hence, $\partial E/\partial\alpha = 0$ if $\chi = 1$ and $\partial E/\partial\alpha > 0$ if $\chi \neq 1$. $\square$

Chapter 6

Backstop Technologies and Directed Technical Change

"*If you do not change direction, you may end up where you are heading.*"

— Laozi (604 B.C.-507 B.C.)

6.1 Introduction

Policy debates during the last decades have witnessed a growing interest in reducing the share of fossil fuels in energy generation. The increasing attention for the sources of energy on which the economy relies is mainly driven by the challenge of combating climate change and the global concern about the sustainability of current living standards. Part of the solution to both the climate change and the sustainability problem may be the invention and implementation of backstop technologies that are able to produce a renewable substitute for non-renewable natural resources like fossil fuels. This chapter is about the important role of technological change in this process. Prospects about future energy generation technologies may affect the time path of fossil fuel consumption, but also the pace and direction of technical progress. Conversely, the speed and direction of technical progress are crucial for the transition from fossil fuels to backstop technologies. We show that the looming introduction of a backstop technology not only speeds up resource extraction, but also reduces current resource-saving technical progress: resource-saving technical change even vanishes completely before the backstop technology is introduced. Moreover, we show that if the costs of generating energy with the backstop technology exceed a certain threshold level, the transition to renewable energy sources does not occur. For intermediate cost levels, the actual implementation of the backstop technology becomes a self-fulfilling prophecy.

To enhance our understanding of how backstop technologies affect the direction and the rate of technical change, and, conversely, how directed technical change influences the energy transition, we need to simultaneously model the extraction of natural resources, the transition to backstop technologies, and the allocation of research and development activities in general equilibrium. For this purpose, we synthesize the neoclassical Dasgupta-Heal-Solow-Stiglitz (DHSS) model of economic growth and non-renewable resources (cf. Dasgupta and Heal, 1974; Solow, 1974a; 1974b; Stiglitz, 1974a; 1974b) and the literature on induced innovations, as introduced by (Hicks, 1932) and more recently formalized in the directed technical change models of Acemoglu 1998; 2002; 2003 and Kiley (1999).[1]

Our main findings are, firstly, that the economy may experience three different regimes. In the first regime, energy generation relies completely on the resource and both types of technological change, labor-augmenting and resource-augmenting, are taking place. The second regime is characterized by pure labor-augmenting technical change (i.e., resource-augmenting technical change equals zero), while energy generation still relies on the resource. In the third regime, energy is generated solely by using the backstop technology and technological progress is purely labor-augmenting. Secondly, compared to the model without a backstop technology, resource extraction is higher initially and the resource extraction path does no longer necessarily have a downward-sloping part. Finally, if the unit cost of the backstop technology exceeds a certain threshold level, the backstop technology will never be introduced. For an intermediate level of unit cost, expectations determine whether the backstop technology will actually become competitive in the future: its implementation becomes a self-fulfilling prophecy.

The literature on directed technical change and non-renewable resources can be divided in two categories. Studies in the first category focus on pollution and (optimal) environmental policies, whereas studies in the second category are mainly concerned with the direction and rate of technical change, and with the development of energy use over time. Goulder and Mathai (2000) belong to the first category. They explore the importance of policy induced directed technical change for the design of environmental policies. Conversely, Di Maria and van der Werf

[1] Hart (2012) generalizes the framework of Acemoglu 1998; 2002; 2003 with respect to knowledge spillovers between the different sectors.

(2008) and Gans (2012) examine the implication of climate protection policies on the direction of technical change. Hart (2008) investigates how the relationship between emissions taxes and technological change is affected by technology spillover effects. Smulders and Di Maria (2012) show that the cost of environmental policy may be larger with induced technical change than without. Grimaud and Rougé (2008) and Acemoglu, Aghion, Bursztyn, and Hemous (2012) determine optimal environmental policy and study the effect of pollution taxes and research subsidies on pollution and technical change in models where clean and polluting inputs are imperfect substitutes. Grimaud, Lafforgue, and Magné (2011) extend this analysis by taking carbon capture and storage (CSS) into account. Newell, Jaffe, and Stavins (1999) and Popp (2002) empirically test the effect of energy prices and government regulations on the direction of technical change. They both find significant effects on energy-saving innovations, at least for some products.

Our analysis, however, is more closely related to the second category. An important contribution here is Smulders and de Nooij (2003), who study the effects of energy conservation policies on the rate and direction of technical change. André and Smulders (2012) use a model of directed technical change and a non-renewable resource to replicate stylized facts concerning the recent development of energy use and energy efficiency over time. Daubanes, Grimaud, and Rougé (2012) investigate the effect of subsidies to R&D activities aimed at improving the productivity of clean substitutes for a polluting non-renewable resource on the resource extraction path. Especially important for our purposes, because of their explicit focus on the direction of technical change, is the paper of Di Maria and Valente (2008), who construct a model in which a non-renewable resource and physical capital are both essential for production. They show that, although there may be capital-augmenting technical progress in the short run, technical change will be purely resource-augmenting along any balanced growth path. In line with this result, Pittel and Bretschger (2010) find that technical change is biased towards the resource-intensive sector at the balanced growth equilibrium of their model economy in which sectors are heterogenous with respect to the intensity of natural resource use. The crucial difference with our model is that we allow for a regime shift in energy usage after which the value of accumulated knowledge in the resource sector vanishes.

In this chapter, we construct a general equilibrium endogenous growth model in which final output is produced with labor and energy services according to a constant elasticity of substitution (CES) production function. In line with the empirical evidence in Koetse, de Groot, and Florax (2008) and van der Werf (2008), energy and man-made factors of production are poor substitutes, i.e. the elasticity of substitution between them is smaller than unity. Labor services are produced with labor and a set of specific intermediate goods. Energy services are either derived from the resource combined with a set of intermediate goods, or generated by the backstop technology. The economy is endowed with a finite stock of the non-renewable resource, that can be extracted without costs. The production of intermediate goods and energy generation with the backstop technology both use final output. Following André and Smulders (2012), technological progress is driven by labor allocated to R&D, which is undertaken by firms in the intermediate goods sector to improve the quality of their products. As a result, there are two types of technical change in the model: labor-augmenting and resource-augmenting technical change. Investment in both types of technical change is driven by profit incentives so that both the rate and the direction of technical progress are endogenously determined. The simplicity of the model allows us to analyze the dynamics and regime switches by using phase diagrams. To quantify the results, we calibrate the model and perform a simulation analysis that makes use of the relaxation algorithm explained in Trimborn, Koch, and Steger (2008).

The remainder of the chapter is structured as follows. Section 6.2 describes the model. Subsequently, the solution procedure is provided in Section 6.3. Section 6.4 discusses the transitional dynamics and regime shifts. Section 6.5 determines the initial resource extraction to complete the solution to the model. Section 6.6 provides a calibration and simulation analysis to quantify the results. Finally, Section 6.7 concludes.

6.2 The Model

The model describes a closed economy that produces a homogeneous final good, with labor and energy services as inputs. Labor services require labor and a set of specific intermediate goods. Energy services can either be produced by combining a non-renewable resource with a set of specific intermediates, or be generated by using a backstop technology that requires the final good as input. The total supply of labor and the initial stock of the non-renewable resource are exogenously given. The productivity of the primary factors of production, labor and the non-renewable resource, depends on the quality of complementary intermediate goods, as in Acemoglu (1998). By investing in in-house R&D, firms can increase the quality of the intermediates that they produce. Infinitely lived households derive utility from consumption. They own the resource stock and the firms. The remainder of this section describes the final good sector, energy generation, the process of research and development, and the household sector in more detail. Mathematical derivations can be found in the Appendix.

6.2.1 Production

6.2.1.1 Final Output

Final output Y is produced using labor services Y_L and energy services Y_E according to the following constant elasticity of substitution (CES) specification:[2]

$$Y = \left[\gamma Y_L^{\frac{\sigma-1}{\sigma}} + (1-\gamma) Y_E^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{6.1}$$

where γ regulates the relative productivity of the inputs and $\sigma \in (0,1)$ denotes the elasticity of substitution between labor and energy services. Profit maximization under perfect competition gives rise to the following relative factor demand function:

$$\frac{\gamma}{1-\gamma}\left(\frac{Y_L}{Y_E}\right)^{-\frac{1}{\sigma}} = \frac{p_{YL}}{p_{YE}}, \tag{6.2}$$

where p_{YL} and p_{YE} are the prices of labor and energy services, respectively.

6.2.1.2 Energy Generation

Energy can be derived from resource services Y_R or generated by backstop technology sector Y_H:

$$Y_E = Y_R + Y_H. \tag{6.3}$$

The generation of energy by the backstop technology requires the final good as input, according to:

$$Y_H = \eta H, \tag{6.4}$$

where $\eta > 1$ is a productivity parameter and H denotes the input of the final good.

[2]Time arguments are omitted if there is no possibility of confusion.

6.2.1.3 Service Sector

Labor and resource services are produced according to the following Cobb-Douglas specification:

$$Y_i = Z_i^{\beta} \int_0^1 q_{ik} x_{ik}^{1-\beta} dk, \tag{6.5}$$

where $i = \{L, R\}$, and $Z_L = L$ and $Z_R = R$ denote the inputs of labor and the resource, respectively. The amount and quality of intermediate good variety k used in sector i is indicated by x_{ik} and q_{ik}, respectively, and the mass of different intermediate goods varieties in each sector is normalized to unity. The resource can be extracted from the initial resource stock S_0, without extraction costs:

$$\dot{S} = -R, \quad R \geqslant 0, \quad \int_0^{\infty} R(t)dt \leqslant S_0. \tag{6.6}$$

Producers in the perfectly competitive service sectors take factor remunerations w_i and intermediate goods prices p_{xik} as given. Their resulting demand for primary inputs and intermediate goods reads, respectively:

$$p_{Yi}\frac{\partial Y_i}{\partial Z_i} = w_i \Rightarrow p_{Yi}\beta Z_i^{\beta-1} \int_0^1 q_{ik} x_{ik}^{1-\beta} dk = w_i, \tag{6.7}$$

$$p_{Yi}\frac{\partial Y_i}{\partial x_{ik}} = p_{xik} \Rightarrow p_{Yi}(1-\beta) q_{ik} \left(\frac{Z_i}{x_{ik}}\right)^{\beta} = p_{xik}. \tag{6.8}$$

6.2.1.4 Intermediate Goods Sector

Each firm in the monopolistically competitive intermediate goods sector produces a unique variety and faces a demand function from the service sector, given by (6.8). Per unit production costs are equal to q_{ik} units of the final good, so that production costs increase proportionally with quality. Firms invest in R&D to increase the quality of their products, according to the following simple specification:[3]

$$\dot{q_{ik}} = \xi_i Q_i D_{ik}, \tag{6.9}$$

where ξ_i is a productivity parameter, $Q_i \equiv \int_0^1 q_{ik} dk$ is the aggregate quality level in sector i, and D_{ik} is labor allocated to R&D at unit cost w_D. The producer of each variety chooses how much to produce and how much to spend on in-house

[3] Dots above a variable denote time derivatives, i.e. $\dot{x} = dx/dt$, and hats denote growth rates, i.e. $\hat{x} = \frac{dx/dt}{x}$.

R&D in order to maximize the net present value of its profit stream, giving rise to the following optimality conditions:

$$p_{xik} = \frac{q_{ik} p_Y}{1-\beta}, \tag{6.10a}$$

$$w_D \geqq \lambda_{ik} \xi_i Q_i \quad \text{with equality if } D_{ik} > 0, \tag{6.10b}$$

$$\frac{\beta}{1-\beta} x_{ik} p_Y = -\dot{\lambda}_{ik} + r\lambda_{ik}, \tag{6.10c}$$

where r is the nominal interest rate and the λ_i's are shadow prices of quality in sector i. Price setting equation (6.10a) shows that firms charge a mark-up over marginal costs. Condition (6.10b) requires that, at an interior solution, the marginal revenue of improving quality is equal to its marginal costs. Equation (6.10c) describes the evolution of the shadow prices of quality. We combine the supply function (6.10a) with the demand for intermediate goods varieties (6.8) to find

$$x_{ik} = x_i = \frac{\theta_i Y (1-\beta)^2}{Q_i}, \tag{6.11}$$

where the θ_i's denote the incomes shares of labor and resource services: $\theta_i \equiv p_{Yi} Y_i / (p_Y Y)$. This expression implies that all intermediate goods producers within the same sector produce the same output level x_i. Combining (6.10b) with (6.10c) and (6.11), we get:

$$r = \beta(1-\beta)\xi_i \theta_i \frac{Y p_Y}{w_D} + \hat{w}_D - \hat{Q}_i, \quad \text{if } D_{ik} > 0. \tag{6.12}$$

Equation (6.12) can be interpreted as a no-arbitrage condition that requires firms to earn the market interest rate on investment in quality improvements. This return depends positively on the relevant incomes shares θ_i (price effect: quality improvements of relatively scarce factors are more valuable) and on the rate of change in the cost of quality improvements $\hat{w}_D - \hat{Q}_i$ (capital gain effect: increasing research costs make current improvements more valuable in the future). The transversality conditions associated with the problem of firms in the intermediate goods sector are:

$$0 = \lim_{z \to \infty} \lambda_L(z) Q_L(z) e^{-\int_0^z r(s)ds}, \tag{6.13}$$

$$0 = \lambda_R(T^*) Q_R(T^*) e^{-\int_0^{T^*} r(s)ds} \Rightarrow \lambda_R(T^*) = 0, \tag{6.14}$$

where T^* denotes the time at which the economy switches from using the non-renewable resource to using the backstop technology. Transversality condition (6.13) requires that the shadow price of quality in the labor service sector vanishes if time goes to infinity, and (6.14) requires the shadow price of quality in the resource service sector to be zero already at the moment the economy switches from the resource to the backstop.

6.2.2 Goods and Factor Market Equilibrium

We define the following factor incomes shares:

$$\begin{aligned} \theta_E &\equiv \tfrac{p_{YE}Y_E}{p_Y Y} \Rightarrow 1-\theta_E = \theta_L \equiv \tfrac{p_{YL}Y_L}{p_Y Y}, \\ \omega_R &\equiv \tfrac{p_{YR}Y_R}{p_{YE}Y_E} \Rightarrow 1-\omega_R = \omega_H \equiv \tfrac{p_{YH}Y_H}{p_{YE}Y_E}. \end{aligned} \tag{6.15}$$

The goods market equilibrium condition is given by:

$$Y = C + \int_0^1 q_{Lk}x_{Lk}dk + \int_0^1 q_{Rk}x_{Rk}dk + H = \frac{C+H}{1-[1-\theta_E(1-\omega_R)](1-\beta)^2}, \tag{6.16}$$

where the second equality uses (6.11) and the definitions (6.15). Labor market equilibrium requires that labor supply L^S equals labor demand from the labor service sector and from R&D: $L^S = L + D$, where $D = D_L + D_R$ and $D_i = \int_0^1 D_{ik}dk$ is aggregate research effort in sector i. Labor is perfectly mobile between the production and the research sector, which gives rise to a uniform wage rate in equilibrium: $w_D = w_L \equiv w$. By using the income share definitions (6.15) in (6.7), labor market equilibrium implies:

$$L^S - D = \beta(1-\theta_E)\frac{p_Y Y}{w}. \tag{6.17}$$

6.2.3 Households

The representative household lives forever, derives utility from consumption of the final good, and inelastically supplies L^S units of labor at each moment. It owns the resource stock with value $w_R S$ and all equity in intermediate goods firms with value $\lambda_L Q_L + \lambda_R Q_R$. The household maximizes lifetime utility

$$U(t) = \int_t^\infty \ln C(z) e^{-\rho(z-t)} dz, \tag{6.18}$$

subject to its flow budget constraint

$$\dot{V} = r(V - w_R S) + \dot{w}_R S + wL^S - p_Y C, \tag{6.19}$$

and a transversality condition:

$$\lim_{z \to \infty} \lambda_V(z) V(z) e^{-\rho z} = 0, \tag{6.20}$$

where ρ denotes the pure rate of time preference, V total wealth, and λ_V the shadow price of wealth. Optimizing behavior of the households gives rise to the following two familiar conditions:

$$\hat{C} = r - \hat{p}_Y - \rho, \tag{6.21}$$

$$\hat{w}_R = r. \tag{6.22}$$

Condition (6.21) is the Ramsey rule, which relates the growth rate of consumption to the difference between the real interest rate and the pure rate of time preference. Condition (6.22) is the Hotelling rule, which requires the resource price to grow at the rate of interest so that resource owners are indifferent between extracting and conserving an additional unit of the resource.

6.3 Solving the Model

In this section, we discuss the solution to the model. We will show that the economy may experience different regimes of technical change. The economy starts in a first regime with labor- and resource-augmenting technical change. Depending on the productivity (or, equivalently, unit cost) of the backstop technology, the economy might subsequently shift to a second and a third regime in which there is only only labor-augmenting (i.e., resource-using) technical change. During the first two regimes, energy generation relies on the non-renewable resource. During the last regime, energy is generated with the backstop technology. Our solution procedure consists of three steps. First, we describe the dynamic behavior of the economy during each regime. Second, we link the three regimes together by using a set of continuity conditions. Finally, we show under which conditions the economy shifts to the second and third regime.

6.3.1 Regime 1: Labor and Resource-Augmenting Technical Change

During the first regime, there are profitable opportunities of quality improvements in both service sectors. As a result, the economy is at an interior equilibrium and experiences both labor- and resource-augmenting technical progress. Energy generation relies completely on the non-renewable resource, because the backstop technology is not yet competitive.

By combining (6.5), (6.7), (6.11), and (6.15), and imposing $\omega_H = Y_H = 0$ we rewrite the relative factor demand from the final good sector (6.2) as

$$\frac{\theta_E}{1-\theta_E} = \left(\frac{w_R}{w_L}\frac{Q_L}{Q_R}\right)^{1-\nu}\left(\frac{1-\gamma}{\gamma}\right)^{\sigma}, \tag{6.23}$$

where $\nu \equiv 1-\beta(1-\sigma)$ so that $\nu \lesseqgtr 1 \Leftrightarrow \sigma \lesseqgtr 1$. Converting (6.23) into growth rates and using the Hotelling rule (6.22), we obtain:

$$\hat{\theta}_E = (1-\nu)(1-\theta_E)\left[r - \hat{w} - (\hat{Q}_R - \hat{Q}_L)\right]. \tag{6.24}$$

Equation (6.24) implies that the energy income share increases if, after correcting for relative productivity changes, the natural resource price grows faster than the wage rate. Converting the labor market equilibrium condition (6.17) into growth rates, using the Ramsey rule (6.21) and imposing $\omega_H = Y_H = 0$, we find:

$$\frac{D}{L^S - D}\hat{D} = \frac{\theta_E}{1-\theta_E}\hat{\theta}_E + \hat{w} - (r-\rho). \tag{6.25}$$

Aggregating (6.9) over all firms in the sector, we find:

$$\hat{Q}_i = \xi_i D_i. \tag{6.26}$$

Using (6.12) for both sectors, we can derive an expression for the endogenous bias in technological change:

$$\hat{Q}_R - \hat{Q}_L = \beta(1-\beta)\frac{p_Y Y}{w}\left[\theta_E(\xi_R + \xi_L) - \xi_L\right]. \tag{6.27}$$

The bias in technological progress depends on the energy income share: if the resource is scarce and therefore the energy income share is large, technological change will be relatively resource-augmenting and *vice versa*. Combining (6.12) and (6.26) with $D = D_L + D_R$, we find an expression for aggregate research effort:

$$r - \hat{w} = \psi^{-1}\left[\beta(1-\beta)\frac{Y p_Y}{w} - D\right], \tag{6.28}$$

where we have defined $\psi \equiv \xi_R^{-1} + \xi_L^{-1}$. Appendix 6.A.5 shows that the real rate of interest equals

$$r - \hat{p}_Y = r - \hat{w}_L - (\hat{p}_Y - \hat{w}) = (1-\theta_E)\left[r - \hat{w} - (\hat{Q}_R - \hat{Q}_L)\right] + \hat{Q}_R. \tag{6.29}$$

By combining (6.2), (6.5), (6.7), (6.11), and (6.24) and imposing $\omega_H = Y_H = 0$, resource extraction growth can be expressed as:

$$\hat{R} = (1-\theta_E)(1-\nu)\left[r - \hat{w} - (\hat{Q}_R - \hat{Q}_L)\right] - \rho = (1-\nu)(r - \hat{p}_Y - \hat{Q}_R) - \rho. \quad (6.30)$$

Resource extraction growth depends positively on the real interest rate and negatively on resource-augmenting technical change, because of a growth and efficiency effect, respectively. The results in this subsection together give rise to the dynamic system described in Proposition 6.1.

Proposition 6.1. *The dynamics of regime 1 at an interior solution (i.e., with $D_L, D_R > 0$) are described by the following two-dimensional system of first-order nonlinear differential equations in θ_E and D:*

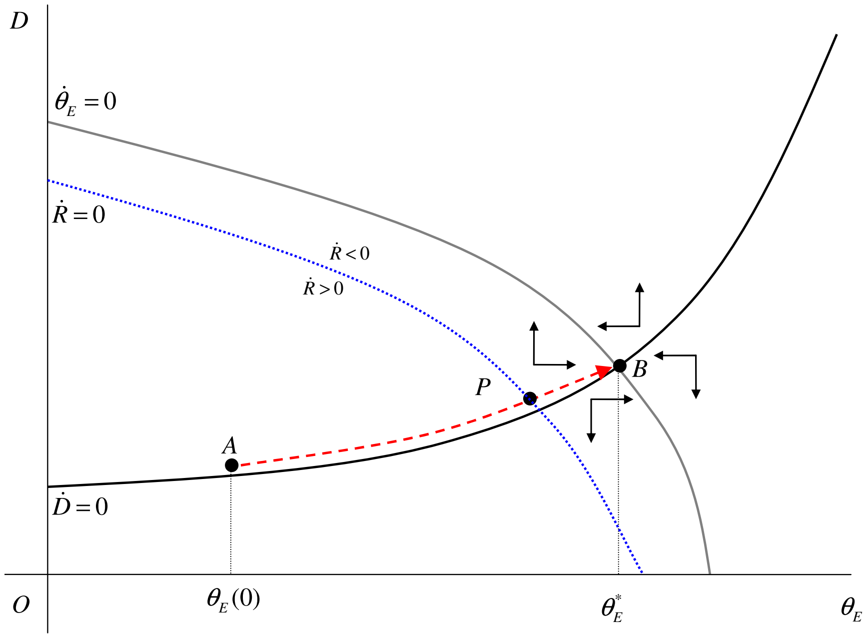
$$\dot{\theta}_E = \theta_E(1-\nu)(1-\beta)\left[(L^S - D)\left(\psi^{-1} - [\theta_R(\xi_R + \xi_L) - \xi_L]\right) - \frac{1-\theta_R}{1-\beta}\frac{D}{\psi}\right], \quad (6.31a)$$

$$\dot{D} = (L^S - D)\left\{\rho - \frac{1-(1-\nu)\theta_E}{\psi}\left[\frac{1-\beta}{1-\theta_E}(L^S - D) - D\right] - \frac{\theta_E(1-\nu)(1-\beta)}{1-\theta_E}[\theta_E(\xi_R + \xi_L) - \xi_L](L^S - D)\right\}. \quad (6.31b)$$

Proof. Substitution of (6.17), (6.27), and (6.28) into (6.24) gives (6.31a), which proves the first part. The second part of the proof follows immediately from substituting (6.17), (6.27), (6.28), and (6.31a) into (6.25). □

Figure (6.1) shows the phase diagram of regime 1 in (θ_E, D)-space. The figure contains three isoclines that we will discuss in turn. First, the income share isocline $\dot{\theta}_E = 0$, derived from (6.31a), gives combinations of θ_E and D for which the income shares are constant. Intuitively, prices of energy and labor services, corrected for productivity changes, grow at the same rate along the income share isocline. For all points below the income share isocline, the return to research and therefore the interest rate is higher than required for constant income shares, so that the relative price of the resource and with it the energy income share increase and *vice versa*. The $\dot{\theta}_E = 0$ line is downward sloping, because an increase in θ_E induces technological change to become relatively more resource saving, which puts downward pressure on the energy income share. To counteract this effect, aggregate research must fall to increase the real rate of interest and therefore the growth rate of the relative price and the income share of the resource. The

Figure 6.1: Phase diagram in (θ_E, D) space: Regime 1 without backstop



Notes: The solid black and gray lines represent the research and income share isoclines, respectively. The dotted line is the extraction isocline. The dashed arrow represents the saddle path that leads to point B.

income share isocline has a vertical asymptote at $\theta_E = \bar{\theta}_E > 0$, to the left of which it tends to minus infinity. The dynamic behavior of θ_E is illustrated by the horizontal arrows in the phase diagram.

Second, the research isocline $\dot{D} = 0$, derived from (6.31b), gives combinations of θ_E and D for which aggregate research effort is constant over time. At points below the research isocline, the real interest rate and output growth are larger than required for constant research. As a result, L tends to increase over time, which leads to declining employment in research over time. The $\dot{D} = 0$ isocline is upward sloping in the neighborhood of $\theta_E = 1$. The reason is that increasing θ_E even further increases the return to research so that in equilibrium the real rate of interest and output growth go up, which tends to induce a flow of labor out of research into production. To counteract this effect, aggregate research D should increase. Although the figure shows a monotonically upward sloping research isocline, this is not necessarily the case. If the productivity of labor in the labor-augmenting research sector is high enough compared to productivity in the resource-augmenting research sector, the $\dot{D} = 0$ may be downward sloping in the neighborhood of $\theta_E = 0$. The reasoning is similar to the case previously discussed: a further decrease in θ_E biases technical change towards the relatively scarce labor services, increasing the return to research and with it the real rate of interest and output growth. To counteract this effect, aggregate research D should increase. The dynamic behavior of D is illustrated by the vertical arrows in the phase diagram.

Third, the extraction isocline $\dot{R} = 0$, derived from (6.30), gives combinations of θ_E and D for which resource extraction is constant over time.[4] At points below the isocline, the real interest rate and with it the growth rates of output and resource demand are higher than required for constant extraction, so that resource extraction increases over time. The extraction isocline has a negative slope, because an increase in θ_E induces technological change to become relatively more resource saving, which puts downward pressure on resource extraction. To counteract this effect, aggregate research must fall to increase the real rate of interest and therefore the growth rate of output and resource demand. Like the income share isocline, the extraction isocline has a vertical asymptote at $\theta_E = \bar{\theta}_E > 0$, to the left of which it tends to minus infinity.

Because it will affect the dynamic behavior of the economy, it is important to determine the relative positions of the isoclines in the phase diagram. In Appendix 6.A.6-6.A.7, we show that the income share and extraction isoclines intersect once, that the vertical intercept of the income share isocline is located above those of the research and extraction isoclines, and that the vertical intercept of the extraction isocline tends to minus infinity if the elasticity of substitution between labor and resource services, σ, goes to unity.

Without the existence of a backstop technology, regime 1 would last forever and the economy would converge along the stable manifold from point A to point B in Figure 6.1.[5] Along the stable manifold, two counteracting forces affect the energy income share. On the one hand, increasing physical scarcity of the resource puts upward pressure on the energy income share. On the other hand, the income share is negatively affected by induced resource-augmenting technical change.[6] These opposing effects exactly offset each other in the steady state equilibrium, resulting in a constant energy income share. In case the stable manifold starts

[4]By substituting (6.17), (6.27), and (6.28) into (6.30), one obtains a differential equation for R in terms of θ_E and D.

[5]The determination of point A will be discussed in Section 6.5.

[6]We focus on a relatively high initial resource stock, so that the economy is located on the part of the stable manifold below the income share isocline, where the energy income share increases because the scarcity effect dominates the induced technical change effect.

out below the extraction isocline, the economy necessarily crosses the extraction isocline before the steady state is reached. As a result, resource extraction can only increase temporarily and peaks when the economy crosses point P in Figure 6.1.

When the existence of a backstop technology is taken into account, the economy does no longer necessarily converge to point B and may eventually shift to another dynamic regime. Both the occurrence of the regime shift and the end point (θ_E, D) in the phase diagram of regime 1 in case of a regime shift depend on the relative price of the backstop technology and intermediate goods and on economic conditions in the subsequent regimes, which will be described below.

6.3.2 Regime 2: Purely Labor-Augmenting Technical Change

In regime 2, energy generation still relies completely on the non-renewable resource. However, the backstop technology will be competitive soon, so that there will be no investment anymore in resource-augmenting technological change, as resource-augmenting technology will be worthless from the moment that the economy switches to the backstop technology.[7] In other words, in this entire regime the shadow price of resource-augmenting technology is strictly lower than the marginal cost of investment in quality improvement of resource complementing intermediates. Therefore, regime 2 is characterized by pure labor-augmenting, i.e. resource-using, technical progress.

Given that $D_R = 0$, we get $D_L = D$, so that (6.26) changes to

$$\hat{Q}_L = \xi_L D. \tag{6.32}$$

Expressions for the return to quality improvements, income share growth, and extraction growth are easily obtained by imposing $\hat{Q}_R = 0$ in (6.12), (6.24), and (6.30), respectively:

$$r - \hat{w} = \beta(1-\beta)\xi_L \theta_L \frac{Y p_Y}{w} - \hat{Q}_L, \tag{6.33a}$$

$$\hat{\theta}_E = (1-\nu)(1-\theta_E)\left[r - \hat{w} + \hat{Q}_L\right], \tag{6.33b}$$

$$\hat{R} = (1-\theta_E)(1-\nu)\left[r - \hat{w} + \hat{Q}_L\right] - \rho = (1-\nu)(r - \hat{p}_Y) - \rho, \tag{6.33c}$$

[7] The existence of regime 2 will be discussed in Section 6.4.

Combining (6.32)-(6.33b) with (6.17), we obtain the dynamic system described in Proposition 6.2.

Proposition 6.2. *The dynamics of regime 2 at an interior solution (i.e., with* $D > 0$*) are described by the following two-dimensional system of first-order nonlinear differential equations in* θ_E *and* D*:*

$$\dot{\theta}_E = \theta_E(1-\nu)(1-\theta_E)\xi_L(1-\beta)(L^S - D), \tag{6.34a}$$

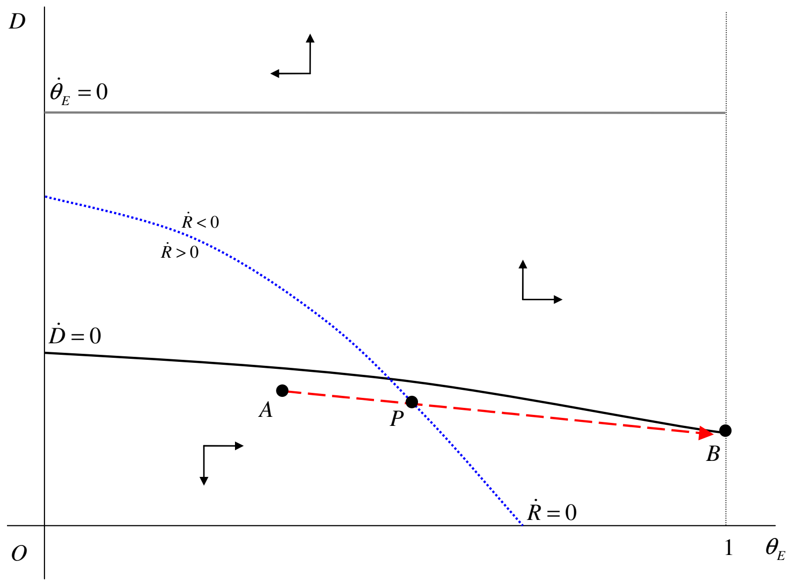
$$\dot{D} = (L^S - D)\left(\rho - [1-\theta_E(1-\nu)]\,\xi_L(1-\beta)(L^S-D) + \xi_L D\right). \tag{6.34b}$$

Proof. Substitution of (6.17), (6.32), and (6.33a), into (6.33b) gives (6.34a). Combining (6.32), (6.33a) and (6.33b) with (6.25) results in (6.34b). □

Figure (6.2) shows the phase diagram of regime 2 in (θ_E, D)-space. We will discuss the income share, research, and extraction isoclines in turn. The income share isocline $\dot{\theta}_E = 0$ is derived from (6.31a) and gives combinations of θ_E and D for which the income shares are constant over time. There is a unique research level associated with constant income shares, so that the income share isocline is horizontal at this specific value of D. Intuitively, the growth rate of the prices of resource and labor services are equal along the $\dot{\theta}_E = 0$ isocline. At points below the isocline, the return to research and therefore the real interest rate is larger so that the price of resource service increases relative to that of labor services, resulting in an increasing energy income share over time and *vice versa.* The dynamic behavior of θ_E is illustrated by the horizontal arrows in the phase diagram.

The research isocline $\dot{D} = 0$ is derived from (6.31b) and gives combinations of θ_E and D for which research is constant over time. It is represented by a downward sloping line, because an increase in θ_E leads to a lower real interest rate and therefore slower output growth. As a result, L tends to decrease over time, which induces a flow of labor from the production to the research sector, causing the innovation rate to rise over time. To counteract this effect, D must decrease thereby increasing the growth rate of labor demand as a result of its combined effect on output growth (through the real interest rate) and the productivity of the factors of production. At points above of the innovation locus, the real interest rate and output growth are lower than in steady state equilibrium, so that L declines and the innovation rate increases over time and *vice versa.* The dynamic behavior of D is illustrated by the vertical arrows in the phase diagram.

Figure 6.2: Phase diagram in (θ_E, D) space: Regime 2 without backstop



Notes: The solid black and gray lines represent the research and income share isoclines, respectively. The dotted line is the extraction isocline. The dashed arrow represents the saddle path that leads to point B.

The extraction isocline $\dot{R} = 0$ is derived from (6.30) and gives combinations of θ_E and D for which resource extraction is constant over time.[8] The $\dot{R} = 0$ line is downward sloping, because an increase in θ_E leads to a lower return to research and therefore a lower real interest rate in equilibrium. As a result, the growth rates of output and resource demand go down. To counteract this effect, D must decrease to enhance the growth of resource demand through its combined effect on the real interest rate and the efficiency of resource extraction. At points above the extraction isocline, the real interest rate and therefore output growth are lower than required for constant extraction, so that extraction growth becomes negative and *vice versa*.

Appendix 6.A.9-6.A.10 shows that the income share isocline is always located above the research and extraction isoclines, and that the vertical intercept of the extraction isocline tends to minus infinity if the elasticity of substitution between labor and resource services, σ, goes to unity.

[8]By substituting (6.17), (6.32), and (6.33a) into (6.33c), one obtains a differential equation for R in terms of θ_E and D.

The dynamics in Figure (6.3) describe the behavior of the economy in regime 2. In a model without the backstop technology available, the economy would converge along the dashed equilibrium path towards point B. Because of the existence of a backstop technology, however, the economy eventually shifts to another regime in which the natural resource will no longer be used. The begin and end point of regime 2 in (θ_E, D)-space depend on economic conditions in this final regime, which will be discussed below.

6.3.3 Regime 3: Hicks-Neutral Technical Change

In regime 3, the resource stock will be depleted and the backstop technology is used instead. As a result, only pure labor-augmenting technological progress is possible.

Final good production is now given by:

$$Y = \left[\gamma Y_L^{\frac{\sigma-1}{\sigma}} + (1-\gamma) Y_H^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{6.35}$$

where Y_H denotes energy generation by the backstop technology, according to (6.4). Perfect competition implies that the price of energy generated with the backstop technology is equal to its marginal production cost: $p_{YH} = \eta^{-1} p_Y$. Using this equality and the income share definition (6.15) in $p_{YH} = p_Y \partial Y / \partial Y_H$, we obtain

$$\theta_E = (1-\gamma)^\sigma \eta^{\sigma-1}. \tag{6.36}$$

Hence, the energy income shares is constant over time and depends negatively on the parameters γ, and η. Substitution of $\hat{\theta}_E = 0$, (6.17), and (6.33a) into (6.25) gives rise to the following differential equation for research:

$$\dot{D} = (L^S - D)\left\{\rho - \xi_L\left[(1-\beta)(L^S - D) - D\right]\right\}. \tag{6.37}$$

Proposition 6.3 summarizes the behavior of the economy in regime 3.

Proposition 6.3. *The dynamic system of regime 3 gives rise to a constant θ_E and D, given by:*

$$\theta_E = (1-\gamma)^\sigma \eta^{\sigma-1}, \tag{6.38a}$$

$$D = \frac{(1-\beta)L^S - \frac{\rho}{\xi_L}}{2-\beta}. \tag{6.38b}$$

Proof. The first part has already been derived in the text. The second part follows because the differential equation (6.37) is unstable in D, so that the economy immediately settles at its steady state level of research, given by (6.38b). □

6.3.4 Linking the Regimes

We link the 3 regimes together by imposing 3 continuity conditions and 1 transversality condition. First, optimal behavior of the resource owners ensures that the resource price is equal to the backstop price at the moment that the resource stock is depleted. This implies a continuous energy price at the regime shift where the economy switches from using the resource to using the backstop technology:

$$\lim_{t \to \uparrow T_{23}} p_{YE}(t) = \lim_{t \to \downarrow T_{23}} p_{YE}(t), \tag{6.39}$$

where T_{23} denotes the time at which the economy shifts from regime 2 to regime 3. Second, the Ramsey rule (6.21) requires consumption to be continuous as long as the real interest rate is finite, which constitutes our second continuity condition at the regime shifts:

$$\lim_{t \to \uparrow T_{ij}} C(t) = \lim_{t \to \downarrow T_{ij}} C(t), \tag{6.40}$$

where $i, j \in \mathbb{N}$ indicate the regimes and T_{ij} denotes the time at which the economy shifts from regime i to regime j. Third, the shadow price of quality in the service sectors λ_k should be continuous at the regime shifts:

$$\lim_{t \to \uparrow T_{ij}} \lambda_k(t) = \lim_{t \to \downarrow T_{ij}} \lambda_k(t), \tag{6.41}$$

where $k = \{R, L\}$. Intuitively, the condition requires that the marginal cost of improving the quality of the intermediate variety at the very end of regime i equals the value of this additional quality at the beginning of the consecutive regime (cf. Valente, 2011). Finally, we use the transversality condition for the shadow price of quality in the resource service sector (6.14) to determine the starting point of the second regime.

6.4 Transitional Dynamics and Regime Shifts

This section implements the solution method described in Section 6.3. We first characterize the solution to the model for the scenario in which the backstop technology will necessarily become competitive eventually (Sections 6.4.1 and 6.4.2). Subsequently, Section 6.4.3 discusses scenarios in which the transition to the backstop technology does not occur, or when the eventual introduction of the backstop technology becomes a self-fulfilling prophecy. Which scenario actually happens, depends crucially on the productivity of the backstop technology.

We use backward induction to determine the equilibrium path in (θ_E, D)-space that starts in regime 1, runs through regime 2, and finally ends as a fixed point in regime 3.[9] Starting with the fixed point in regime 3, we can use the continuity conditions to find the end point of regime 2. Subsequently, we use the transversality condition for the shadow price of quality in the resource service sector to find the starting point of regime 2. Then, the continuity conditions will give us the end point of regime 1, after which we close the model by solving for the initial value of the energy income share that clears the non-renewable resource market.

6.4.1 Shift from Resource to Backstop

At the shift from regime 2 to regime 3, the economy switches from generating energy with the non-renewable resource to producing energy with the backstop technology. Condition (6.40) requires that consumption is continuous at this switching instant. Using the goods market equilibrium condition (6.16), continuity of consumption requires

$$Y_{23}^{-} = (1 - \theta_{E3}) Y_3^{+}, \tag{6.42}$$

where we have imposed $H = 0$ and $\omega_R = 1$ on the left hand side, and $\omega_R = 0$ and $H = \theta_E Y$ on the right hand side. By using definition (6.15) we rewrite output as:

$$Y = Y_L \left[\gamma + (1 - \gamma) \left(\frac{\theta_E}{1 - \theta_E} \frac{p_{YL}}{p_{YE}} \right)^{\frac{\sigma - 1}{\sigma}} \right]^{\frac{\sigma}{\sigma - 1}}. \tag{6.43}$$

Using the continuity of prices and income shares, a jump in Y must be proportional to a jump in Y_L. Furthermore, it follows from (6.5) and (6.11) that a jump in Y_L is proportional to a jump in L. Combining this with (6.42), the continuity condition becomes:

$$\frac{L^S - D_3^{+}}{L^S - D_{23}^{-}} = \frac{1}{1 - \theta_E} \Rightarrow D_{23}^{-} = D_{23}^{+}(1 - \theta_E) + \theta_E L^S. \tag{6.44}$$

Aggregate research D is constant over time in regime 3, so that D_3^{+} is given by the right-hand-side of (6.38b). Substitution of (6.38b) into (6.44) gives the level of research at the very end of regime 2, such that the corresponding upward jump

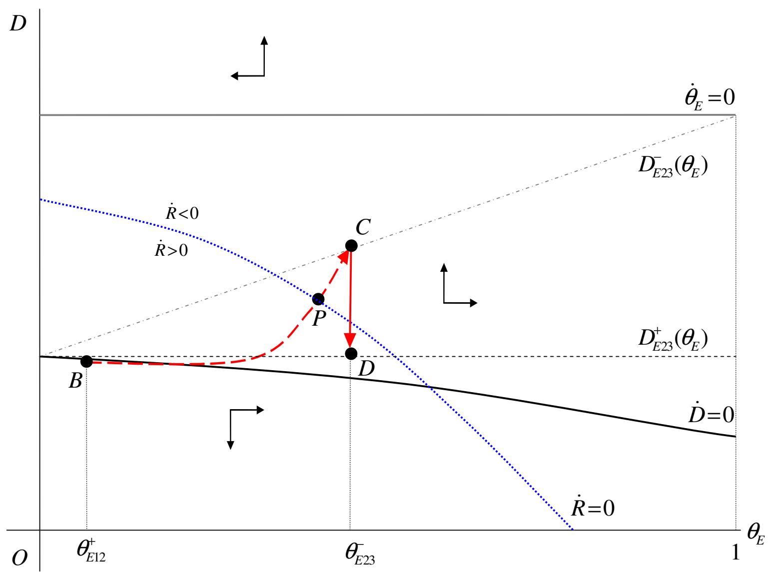
[9] Appendix 6.A.12 shows that there does not exist a regime of simultaneous use of the resource and the backstop technology.

in output is exactly high enough to keep consumption continuous at the regime shift:

$$D_{23}^{-} = \frac{\xi_L L^S(1-\beta+\theta_E) - \rho(1-\theta_E)}{\xi_L(2-\beta)}. \tag{6.45}$$

The energy income share at the end of regime 2, θ_{23}^{-}, is pinned down by equation (6.38a). Hence, we have determined the point $(\theta_{E23}^{-}, D_{23}^{-})$ to which the economy converges during the second regime. Figure 6.3 shows the equilibrium path leading

Figure 6.3: Phase diagram in (θ_E, D) space: Regime 2



Notes: The solid black and gray lines represent the research and income share isoclines, respectively. The dotted line is the extraction isocline. The dashed black and dashed-dotted gray lines give, respectively, D_{23}^{+} and D_{23}^{-} as functions of θ_E. The dashed arrow represents the equilibrium path that leads to point B.

to point D. Along the equilibrium path, the resource income share is increasing over time. Aggregate research may be declining initially, but it increases during the run-up to the backstop technology until the moment of the regime shift. As soon as the economy hits point C, aggregate research jumps down to point D. The reason is that consumers want to prevent a downward jump in consumption at the regime shift, when energy generation with the backstop technology starts using output. Put differently, by investing relatively more now, consumers effectively shift part of the resource wealth to the backstop era.

In Figure 6.3, the equilibrium path crosses the extraction isocline at point P, so that resource extraction first increases, peaks at point P and then declines over time until the regime shift. The location of point B in the figure, which marks the regime shift from an era of both resource and labor-augmenting technological progress to a regime of purely labor-augmenting technical change, will be determined below.

6.4.2 Shift to Purely Labor-Augmenting Technical Change

According to transversality condition (6.14), the shadow price of resource-augmenting technical change should be zero at the end of regime 2. Intuitively, after the regime switch at T_{23}, the resource will not be used anymore so that resource-augmenting technology is worthless from that moment onward. Optimality condition (6.10b) requires that the marginal cost is equal to the marginal value of quality improvement in regime 1. In regime 2, however, this equality does no longer hold: the marginal cost is now larger than the marginal value. We exploit this distinction between the two regimes to determine the time of the shift from regime 1 to regime 2, T_{12}.

First, we define the ratio of marginal value and cost of quality improvements as follows:

$$\mu \equiv \frac{\xi_R Q_R \lambda_R}{w}. \tag{6.46}$$

At the end of regime 1, (6.10b) holds with equality, so that $\mu(T_{12}^-) = 1$. At the end of regime 2, transversality condition (6.14) implies $\mu(T_{23}^-) = 0$. Using the continuity condition for λ_R, (6.41) with $i = R$ and (6.10b), we find the value for μ at the beginning of regime 2:[10]

$$\lambda_R(T_{12}^-) = \lambda_R(T_{12}^+) \Rightarrow \mu(T_{12}^-) = \mu(T_{12}^+). \tag{6.47}$$

As a result, for regime 2 we have the following begin and end condition:

$$\mu(T_{12}^+) = 1, \tag{6.48a}$$

$$\mu(T_{23}^-) = 0. \tag{6.48b}$$

Combining (6.10b), (6.10c), (6.11), and (6.46) we find a differential equation for μ:

$$\dot{\mu} = (r - \hat{w})\mu - \xi_R \beta (1-\beta)\theta_E \frac{p_Y Y}{w} \tag{6.49}$$

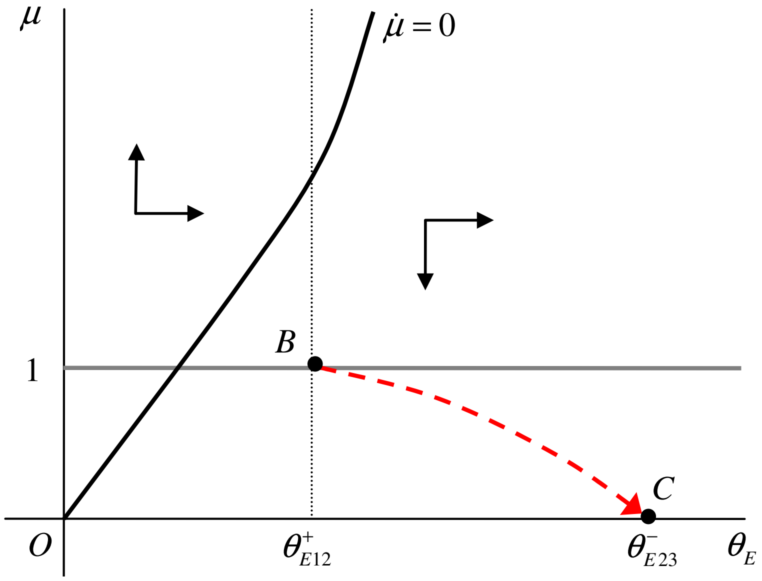
[10] The continuity of w follows from (6.12).

Substitution of (6.12) and (6.17) into (6.49), we obtain a differential equation for μ in terms of θ_E and D:

$$\dot{\mu} = \mu\left[(1-\beta)\xi_L(L^S - D) - \xi_L D\right] - \frac{\theta_E}{1-\theta_E}\xi_R(1-\beta)(L^S - D). \tag{6.50}$$

Because the time paths for θ_E and D are already determined, together with the begin and end conditions (6.48a)-(6.48b), equation (6.50) can be used to find the energy income share at the beginning of regime 2. As a result, this procedure pins down the points $(\theta^+_{E12}, D^+_{12})$ and, because of the continuity conditions, $(\theta^-_{E12}, D^-_{12})$. Figure 6.4 shows the equilibrium path leading to point C. Regime 2 starts at point B, where $\mu = 1$ and investment in resource-augmenting technical progress is still profitable. As θ_E increases further, however, the switch to the backstop technology (when resource-augmenting technology becomes obsolete) is so close that μ falls short of unity, so that D_R jumps down to zero.[11] This event marks the beginning of regime 2. Having determined this point $(\theta^+_{E12}, D^+_{12})$, we have also pinned down the point to which the economy should converge during regime 1.

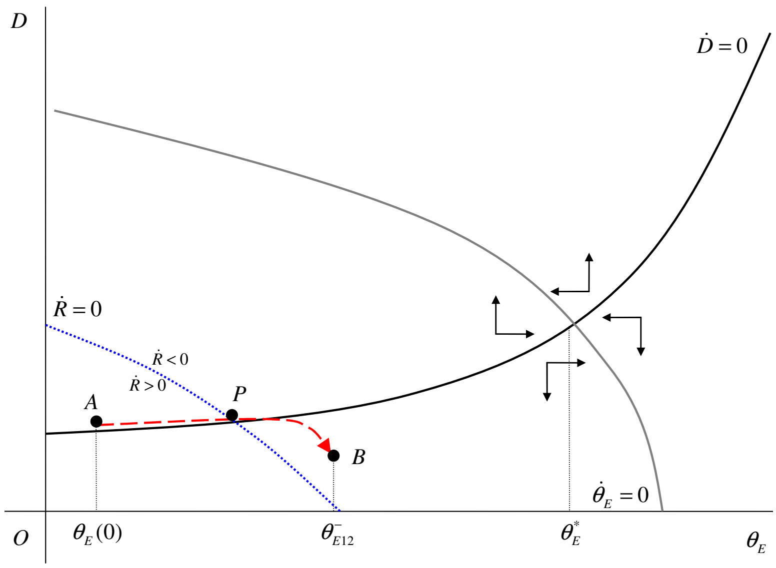
Figure 6.4: Phase diagram in (θ_E, μ) space: Regime 2



Notes: The solid black line represents the $\dot{\mu} = 0$ isocline. The gray line corresponds with $\mu = 1$. The dashed arrow represents the equilibrium path that leads to point C.

[11]Intuitively, the downward jump in D_R occurs because $\dot{Q}_R$ is linear in D_R (see (6.9)), so that the marginal cost (in terms of required researchers) of quality improvement does not depend on D_R. The proof for the downward jump in D_R can be found in Appendix 6.A.13.

Figure 6.5: Phase diagram in (θ_E, D) space: Regime 1



Notes: The solid black and gray lines represent the research and income share isoclines, respectively. The dotted line is the extraction isocline. The fat dots represent the equilibrium path that leads to point B.

Figure 6.5 shows the equilibrium path that leads to point B in the (θ_E, D)-plane. The energy income share is increasing over time along this path. Initially, the resulting price effect induces an increase in profits per unit of quality in the resource sector, leading to an increase in resource-augmenting technical change. This effect is strong enough to outweigh the decreasing amount of labor-augmenting research (as the labor income share declines) so that aggregate research increases. However, as the introduction of the backstop technology comes closer, the remaining time during which quality improvements in the resource sector generate profits becomes smaller. As a result, the increase of resource-augmenting research diminishes and aggregate research start to decline over time until the end of regime 1, when resource-augmenting technical change stops. This decline of aggregate research at the end of regime 1 necessarily occurs if the beginning of regime 2 is located below the research isocline, as shown Figure 6.3.

The starting point A on the equilibrium path depends on the initial resource stock. In Section 6.5, we will derive the resource market clearing condition that determines the initial energy income share and with it, given that we know the equilibrium path, the location of point A.

6.4.3 Backstop Abstinence and Self-Fulfilling Prophecy

In this section, we discuss the scenarios in which the backstop technology will never become competitive or when the implementation of the backstop technology is a self-fulfilling prophecy. Proposition 6.4 summarizes the results of this section.

Proposition 6.4. *Assuming that $\theta_E(0) < \theta_E^*$, the following three scenarios of backstop technology implementation can be distinguished:*

1. *if $\theta_E^* > \theta_{E23}^+$, the backstop technology will eventually be implemented;*
2. *if $\theta_E^* < \theta_{E23}^+$ and $\theta_{E12}^- > \bar{\theta}_E$, the backstop technology will never be implemented;*
3. *if $\theta_E^* < \theta_{E23}^+$ and $\theta_{E12}^- < \bar{\theta}_E$, the implementation of the backstop technology becomes a self-fulfilling prophecy;*

where θ_E^* denotes the energy income share at the intersection of the research and income share isoclines in regime 1, $\theta_{E23}^+ = (1-\gamma)^\sigma \eta^{\sigma-1}$ is the energy income share in regime 3, and $\bar{\theta}_E \equiv \theta_E|_{\dot{\theta}_E=0, D=D_{12}^-}$ in regime 1.[12]

Proof. We compare two possible paths in the (θ_E, D) phase diagram: the first one (which we will call 'conservative') is the path in regime 1 that leads to the intersection of the income share isocline and the research isocline in the (θ_E, D)-plane. This corresponds to the saddle path of the model without a backstop technology (see Figure 6.2). The second one (which we will call 'progressive') is the equilibrium path that ultimately leads to the implementation of the backstop technology, as described in Sections 6.4.1 and 6.4.2.

In scenario (i), the conservative path cannot be an equilibrium, because this path necessarily intersects the line $\theta = \theta_{23}^-$, so that along part of the conservative path the inequality $\theta_E > \theta_{E23}^+$ holds. As a result, the non-renewable resource is relatively more expensive than the backstop technology. Hence, the resource will not be used anymore and the dynamics of the economy are no longer described by the dynamic system of regime 1. The progressive path is the only remaining equilibrium. This is the scenario described in Sections 6.4.1 and (6.4.2).

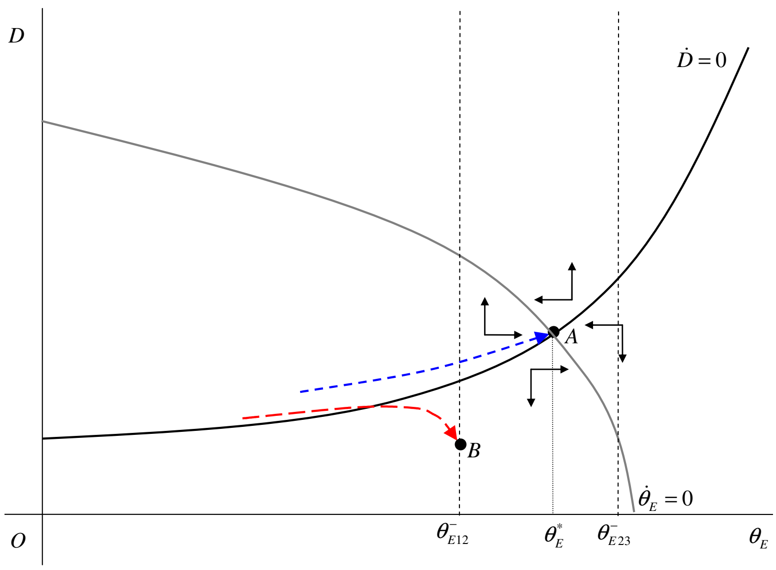
In scenario (ii), the progressive path cannot be an equilibrium, because the end point of regime 1 would be located to the right of the income share locus. This point can only be approached if $\theta_E(0) > \bar{\theta}_E$. However, we have assumed that the

[12]The expression for θ_E^* in terms of parameters can be found in Appendix 6.A.6.

initial resource stock is large enough to have $\theta_E(0) < \theta_E^* < \bar{\theta}_E$. The conservative path can be an equilibrium, because it does not intersect the line $\theta_E = \theta_{E23}^-$, so that along the entire path the inequality $\theta_E < \theta_{E23}^+$ holds. As a result, the non-renewable resource is relatively cheaper than the backstop technology and the dynamics of the economy are accurately described by the dynamic system of regime 1.

In scenario (iii), both the conservative and the progressive path can be an equilibrium. The conservative path does not intersect the line $\theta_E = \theta_{E23}^-$, so that along the entire path the necessary condition for regime 1, $\theta_E < \theta_{E23}^+$, holds. At the same time, the progressive path may be an equilibrium, as the energy income share increases to θ_{E23}^+ during regime 2, which starts as soon as the economy in regime 1 has converged to $(D_{12}^-, \theta_{E12}^-)$. Hence, in this scenario there are multiple equilibria, as shown in Figure 6.6. Expectations determine which equilibrium path will be chosen, so that the implementation of the backstop technology is a self-fulfilling prophecy. □

Figure 6.6: Phase diagram in (θ_E, D) space: Scenario (iii)



Notes: The solid black and gray lines represent the research and income share isoclines, respectively. The dashed arrows represent the conservative and progressive equilibrium path that lead to point A and B, respectively

The intuition for the self-fulfilling prophecy in scenario (iii) is that both paths are sensible, given that they are expected by investors. If investors expect that the backstop technology will be too expensive to implement, they foresee that the economy will rely on the non-renewable resource forever. Hence, resource-augmenting technical change is profitable and will occur at a high rate. As a result, the resource indeed remains relatively cheaper than the backstop technology. Conversely, if investors expect that the backstop technology is going to replace the non-renewable resource in the future, they will invest less in resource-augmenting technical change, because their investments will become worthless as soon as the economy shifts to the backstop technology. As a result, resource-augmenting technical change will be low and eventually fall to zero, so that the backstop technology indeed becomes competitive and will be implemented.

6.5 Initial Conditions

Although we have constructed the equilibrium path in (θ_E, D)-space that runs through regime 1 and 2 and ends at a fixed point in regime 3, we still have to determine the initial point along this path to complete the solution to the model.[13] We can find this initial point by exploiting the fact that total resource extraction over time should be equal to the initial stock of the resource, or equivalently, that the resource stock should be equal to zero at the moment the economy shifts from using the resource to using the backstop (i.e., at time T_{23}).

In order to do so, we first need a differential equation for the reserve-to-extraction rate $y \equiv S/R$ in terms of y, θ_E, and D. Appendix 6.A.14 derives the expressions for the following differential equations in regime 1 and regime 2, respectively:

$$\dot{y} = -y(1-\theta_E)(1-\nu)\left[\frac{1-\beta}{1-\theta_E}(L^S - D)\left\{\psi^{-1} - (\theta_E(\xi_R + \xi_L) - \xi_L)\right\} - \psi^{-1}D\right], \tag{6.51a}$$

$$\dot{y} = -y(1-\theta_E)(1-\nu)\xi_L(1-\beta)(L^S - D) + \rho y - 1. \tag{6.51b}$$

Because we can plug in the already determined time paths for θ_E and D, we can use these differential equations to find a unique equilibrium path in (θ_E, y)-space that leads to a zero reserve-to-extraction rate at the time of the regime shift to the backstop technology. We define this equilibrium path as $y = g(\theta_E)$. Subsequently,

[13] In this section, we only discuss the initial conditions for scenario (i) of Proposition 6.4, in which the backstop technology will necessarily be implemented. The case in which the economy remains in regime 1 forever is simpler and can be solved in a similar way.

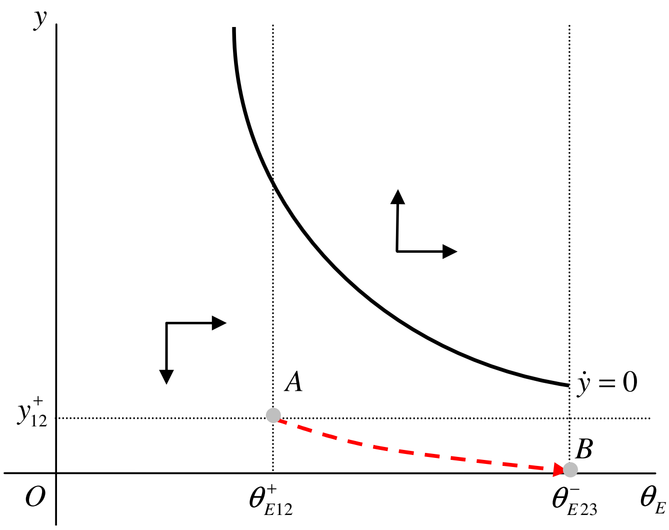
by defining the function $D = f(\theta_E)$ as the equilibrium path in (θ_E, D)-space, we can substitute this function $f(\theta_E)$ in the relative factor demand function that follows from the combination of (6.5) and (6.23), to derive a relationship between the initial θ_E and y:

$$\frac{\theta_E(0)}{1-\theta_E(0)} = \left(\frac{1-\gamma}{\gamma}\right)^{\frac{\sigma}{\nu}} \left(\frac{S_0}{y(L^S - f(\theta_E))} \frac{Q_R(0)}{Q_L(0)}\right)^{\frac{\nu-1}{\nu}}. \tag{6.52}$$

The initial income share $\theta_E(0)$ now follows from the intersection of $g(\theta_E)$ and the initial relative factor demand function in (θ_E, y)-space.

Working backward in time, we first construct the equilibrium path for y in regime 2 and subsequently extend it into regime 1. By imposing $y(T_{23}) = 0$ and using the already determined time paths of θ_E and D, the differential equation (6.51b) gives a unique equilibrium path in (θ_E, y)-space.

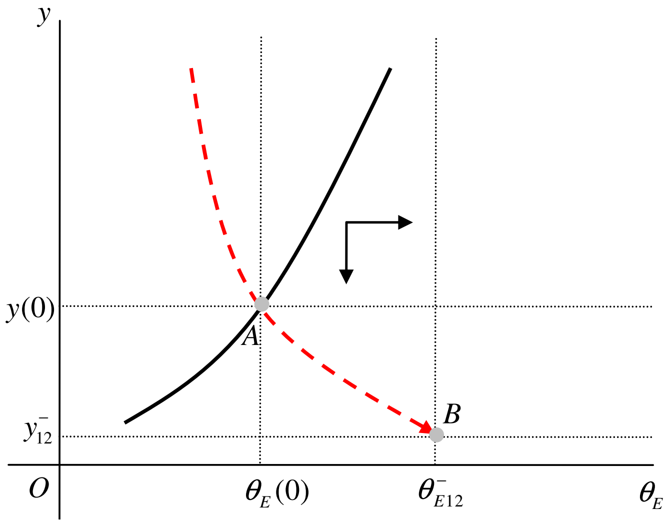
Figure 6.7: Phase diagram in (θ_E, y) space: Regime 2



Notes: The dashed arrow represents the unique equilibrium path that leads to point B, governed by the dynamic system for θ_E, $D = f(\theta_E)$, and y. The solid line is the $\dot{y} = 0$ locus, which gives combinations of θ_E and y such that y is constant over time.

Given that we know θ^+_{E12}, we can use the equilibrium path $g(\theta_E)$ to determine y^+_{12}. Figure 6.7 illustrates this procedure. It shows the phase diagram for the reserve-to-extraction rate in regime 2. The solid line represents the $\dot{y} = 0$-locus and the dashed arrow gives the equilibrium path for y. Hence, during regime 2, the reserve-to-extraction rate moves along the equilibrium path from point A to

Figure 6.8: Phase diagram in (θ_E, y) space: Regime 1



Notes: The dashed arrow represents the unique equilibrium path that leads to point B, governed by the dynamic system for θ_E, D, and y. The solid line gives the relationship between $\theta_E(0)$ and $y(0)$ according to the relative factor demand equation (6.52). The $\dot{y} = 0$-locus is left out to keep the diagram clear.

point B. The dynamic behavior of θ_E and y is illustrated by the solid horizontal and vertical arrows, respectively.

Because of the continuity of the energy income share θ_E and the total research effort D at T_{12} the reserve-to-extraction rate y should also be continuous at T_{12}, i.e. $y_{12}^- = y_{12}^+$. Therefore, having determined the point $(\theta_{E12}^-, y_{12}^-) = (\theta_{E12}^+, y_{12}^+)$, we can use the differential equation (6.51a) together with the already determined time paths of θ_E and D to pin down the equilibrium path of y in regime 1 leading to this end point. The phase diagram in Figure 6.8 illustrates this. The constructed equilibrium path is represented by the dashed arrow. The solid line in the figure shows the relationship between the initial values of θ_E and y, which is given in (6.52). The intersection of (6.52) with the constructed equilibrium path in (θ_E, y)-space, determines the initial point $[\theta_E(0), y(0)]$ that is consistent with factor market equilibrium and with complete depletion of the resource stock. Hence, during regime 1, the reserve-to-extraction rate starts at point A and moves along the equilibrium path to point B in Figure 6.8. The dynamic behavior of θ_E and y is illustrated by the solid horizontal and vertical arrow, respectively.

6.6 Numerical Illustration

In this section, we quantify the results of the model by performing a numerical analysis. We first calibrate the model to match data on energy expenditures, reserve-to-extraction rates, and consumption growth in modern industrialized economies. To check the robustness of the model, we also simulate a specification of the model in which the non-renewable resource and the backstop technology are good but imperfect instead of perfect substitutes.[14] Subsequently, we discuss the simulation outcomes of three different scenarios.

6.6.1 Calibration

In line with empirical evidence, we presume that the elasticity of substitution between labor and energy is smaller than unity. In a meta-analysis Koetse, de Groot, and Florax (2008) find a cross-price elasticity between capital and energy in the United States of 0.383 in the short run and 0.520 in the long run. We take the average of these values and impose $\sigma = 0.45$. The parameter β is the output elasticity of the primary factors, labor and the non-renewable resource, in both service sectors. Our value of 0.80 lies within the range of the labor income shares reported in Gollin (2002b) and is in line with the share of fossil fuel consumption in total energy consumption in the OECD countries in 2010. We set the rate of pure time preference ρ to 0.01 and choose $\gamma = 0.50$ for the final good production function parameter. The backstop productivity parameter η is fixed at 10. The initial stocks of quality in both sectors Q_{L0}, Q_{R0} and the labor supply L^S are normalized to unity.

We choose an initial non-renewable resource stock of 1250 to obtain an initial energy income share of 8.8 percent, equal to the average energy expenditure share in GDP over the period 1970-2009 in the United States (U.S. Energy Information Administration, 2011). By choosing the research productivity parameters $\xi_L = 0.165$ and $\xi_R = 0.90$, we get an initial yearly consumption growth rate of 1.7 percent, in line with the average yearly growth rate of GDP per capita in the United States over the period 1970-2011 (The Conference Board, 2011). The reserve-to-production ratios for oil, natural gas, and coal in 2008 were 44, 58,

[14] In the imperfect substitution specification, the elasticity of substitution between the resource and the backstop is set to $\alpha = 50$.

and 127, respectively (U.S. Energy Information Administration, 2012).[15] Our implied initial reserve-to-extraction rate $y(0)$ of 74 lies within this range. The backstop-resource price ratio $p_{YH}(0)/p_{YR}(0)$ is initially equal to 3.8 and gradually declines towards unity. Our calibration implies that $\theta_{23}^{+} < \theta^{*}$, so that the backstop technology will eventually become competitive. The simulated model gives rise to roughly 80 years of resource use before the backstop technology is implemented. Resource-augmenting technical change will disappear after the first quarter of this era.

6.6.2 Results

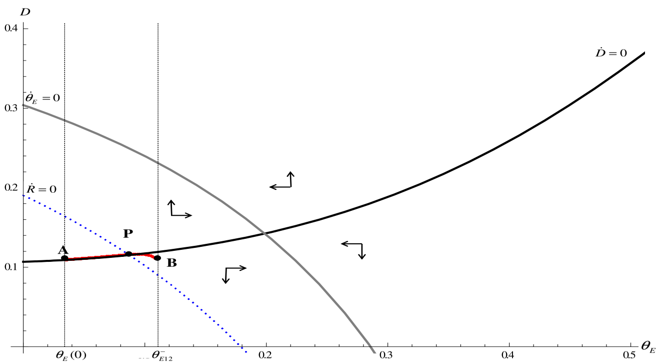
Figure 6.9 shows the phase diagrams of the calibrated model. Panels (a) and (b) correspond to regime 1 and 2, respectively. Panel (c) shows the phase diagram in (θ_E, μ)-space, which is used to determine the starting point of regime 2. Finally, panel (d) shows the phase diagram for the model without a backstop technology. The equilibrium paths are given by the fat dotted lines in the four panels. The economy starts at point A in panel (a) and moves along the equilibrium path, crosses the extraction isocline at point P and continues until point B, which is also shown in panel (b). After the regime shift, the economy gradually moves along the equilibrium path from this point B in panel (b), passes the extraction isocline at point P, and finally reaches point C. As soon as point C is reached, total research jumps down from point C to point D. Panel (c) illustrates that the energy income share at the time of the first regime shift, θ_{E12}^{+}, can be determined by using the intersection point of the equilibrium path and the horizontal $\mu = 1$ line. Finally, panel (d) shows that an economy without a backstop technology, will move along the indicated equilibrium path from point A to point B, where the income share and research isoclines intersect.

Figure 6.10 depicts the time paths of six variables of interest. The solid lines represent the benchmark scenario. To illustrate the importance of taking the existence of a backstop technology into account, the gray line shows the time paths for an economy without a backstop technology that is similar to the benchmark economy in all other respects. As a robustness check, the dashed lines give the results for a model in which the non-renewable resource and the backstop technology are good, but imperfect instead of perfect substitutes. The time paths generated by

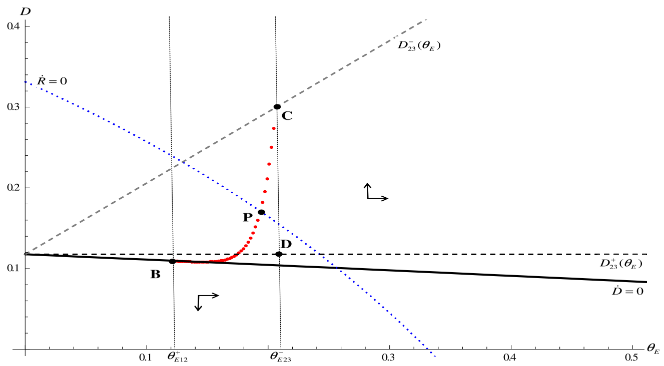
[15] For 2011, BP (2012) reports reserve-to-production rates of 54, 60, and 112 for oil, natural gas, and coal, respectively.

Figure 6.9: Phase Diagrams of the Calibrated Model

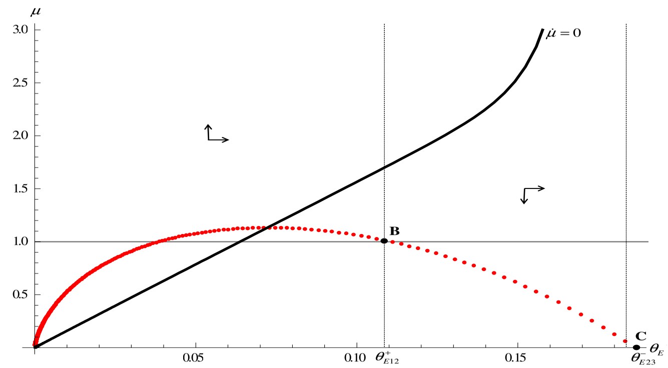
Panel (a): Regime 1



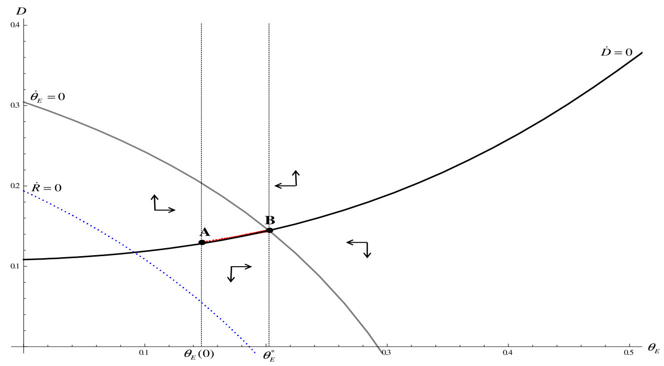
Panel (b): Regime 2



Panel (c): Regime 2: Determination of Starting Point

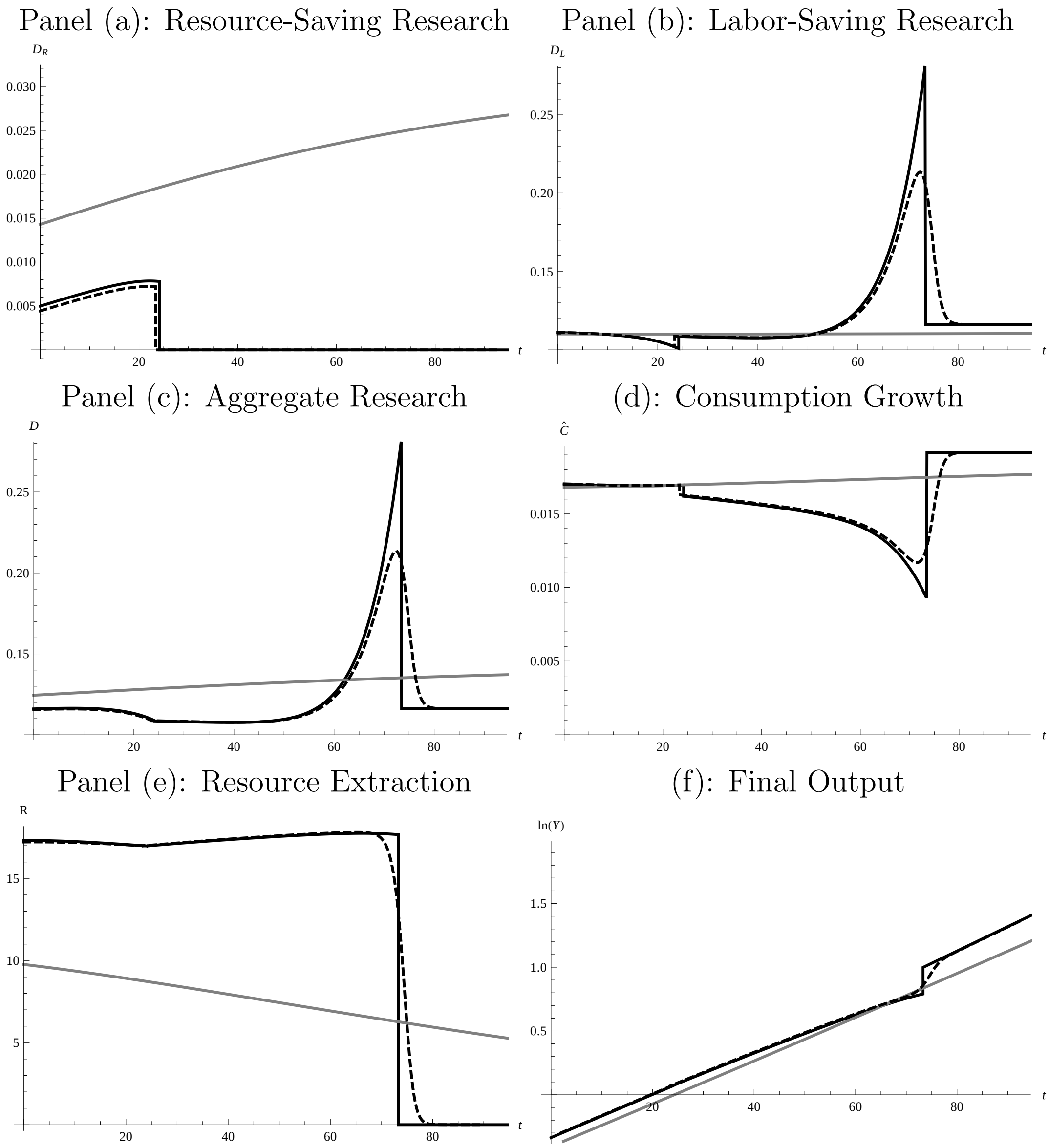


Panel (d): Model without backstop technology



Notes: The dotted lines are the extraction isoclines. The fat dots represent the equilibrium paths. In panels (a), (b), and (d), the solid black line represents the research isocline. In panels (a) and (d), the gray line represents the income share isocline, which is left out in panel (b). The dashed black and gray lines in panel (b) give, respectively, D_3^+ and D_{23}^1. In panel (c), the solid black line is the $\dot{\mu}=0$ isocline. The underlying parameter values are: $L^S=1$, $\alpha=50$, $\beta=0.80$, $\gamma=0.50$, $\eta=10$, $\rho=0.01$, $\sigma=0.45$, $\xi_L=0.165$, and $\xi_R=0.90$. The initial quality levels $Q_L(0)$ and $Q_R(0)$ are equal to 1. The initial resource stock S_0 is set to 1250 in scenarios 1 and 2 to obtain $\theta_E(0)=0.088$ in scenario 1. In the third scenario, the initial resource stock is chosen such that $\theta_E(0)=0.088$.

Figure 6.10: Transitional Dynamics



Notes: The solid line represents scenario 1, in which a backstop technology that provides a perfect substitute for the resource is available. The gray line represents scenario 2, in which there is no backstop technology available. The solid line represents scenario 3, in which a backstop technology that provides a good, but imperfect substitute for the resource is available. Parameters are set to: $L^S = 1$, $\alpha = 50$, $\beta = 0.80$, $\gamma = 0.50$, $\eta = 10$, $\rho = 0.01$, $\sigma = 0.45$, $\xi_L = 0.165$, and $\xi_R = 0.90$. The initial quality levels $Q_L(0)$ and $Q_R(0)$ are equal to 1. The initial resource stock S_0 is set to 1250 in scenarios 1 and 2 to obtain $\theta_E(0) = 0.088$ in scenario 1. In the third scenario, the initial resource stock is chosen such that $\theta_E(0) = 0.088$.

the imperfect substitutes model are smoother, but otherwise quite similar to the ones that result from our benchmark model.

Panel (a) of Figure 6.10 shows that the availability of a backstop technology leads to a smaller amount of research in the resource service sector. Panel (b) indicates that labor saving research jumps up as the economy shifts to the regime without resource-augmenting technical change. Panel (c) delineates the non-monotonic development of aggregate research compared to the monotonically increasing research efforts in the model without a backstop technology. Panel (d) shows the repercussions of the reallocations of labor between the production and the research sector. As illustrated in panel (e), resource extraction is initially declining, starts to increase as soon as the economy shifts to regime 2, then peaks just before the start of regime 3, when the resource stock is depleted and extraction jumps to zero. In the model without a backstop technology, resource extraction is lower initially and decreases monotonically over time. Finally, panel (f) shows the jump in output that materializes at the second regime shift, when energy generation with the backstop technology commences.

6.7 Conclusion

This chapter has investigated the interaction between the existence of backstop technologies (technologies capable of producing renewable substitutes for non-renewable resources) and the rate and direction of technical change. For this purpose, we have constructed a growth model with a non-renewable resource and a backstop technology in which profit incentives determine both the rate and the direction of technical change endogenously. We take into account that natural resources and man-made factors of production are poor substitutes and that energy generation with the backstop technology is costly. The model is solved analytically and we visualize its transitional dynamics and regime shifts in phase portraits of the different regimes. We quantify the results by calibrating the model and performing a simulation analysis. Moreover, we show that the results are robust to relaxing the assumption of perfect substitutability between the non-renewable resource and the backstop technology.

We find that the economy may experience two consecutive regimes of energy generation. Initially, energy generation relies completely on the resource. Depending on the productivity of the available backstop technology, the economy may shift to a regime in which the resource stock is depleted and only the backstop technology will be used to produce energy. In this scenario, short-run resource extraction will be higher than in a model without the backstop technology. The results of this scenario are also relevant for the literature on the 'Green Paradox', because we find that the transition to a backstop technology not only leads to more aggressive resource extraction in the beginning, but also reduces resource-saving technical change compared to an economy without a backstop technology available: the increase in energy efficiency even ceases before the backstop technology becomes competitive. Hence, there are also two consecutive regimes of technical change. Initially, both labor and resource-augmenting technical change are taking place. Subsequently, a second regime with purely labor-augmenting technical change commences.

Due to the endogeneity of the direction of technical change, the transition to the backstop technology does not take place in all scenarios. If the productivity of the backstop technology is low enough, the economy remains in the resource regime forever: the backstop technology will not become competitive. For intermediate values of the backstop technology productivity, the implementation of the backstop technology is a self-fulfilling prophecy: if investors expect energy generation to rely upon the resource forever, investment in resource-augmenting technical change is attractive so that resource-augmenting technical change is high and the resource indeed remains relatively cheaper than the backstop technology. Conversely, if investors expect the backstop technology to be implemented in the future, resource-augmenting technical change becomes unattractive and eventually drops to zero, so that the backstop technology indeed will become competitive in the future.

In our analysis, we have abstracted from stock-dependent extraction costs. To shed light on optimal environmental policy, these should be introduced together with pollution from the combustion of the non-renewable resource. An extension in this direction is especially interesting in the light of the multiple equilibria that may exist if the backstop technology is relatively expensive (i.e., relatively unproductive). Furthermore, the effects of including a separate type of backstop technology improving technical change could be investigated in future work.

6.A Appendix

This appendix contains the derivations of the mathematical results in the chapter. It first derives the optimality conditions for firms and households. Second, expressions for the relative income shares and the real interest rate will be derived. Finally, some important properties of the differential equations and the isoclines in the dynamic system will be discussed.

6.A.1 Final Output

Profit of firms in the final output sector are given by:

$$p_Y Y(Y_L, Y_E) - p_{YL} Y_L - p_{YE} Y_E \tag{A.6.1}$$

where the function for Y is specified in (6.1). Profit maximization gives rise to the following first-order conditions:

$$p_{YL} = p_Y \left[\gamma Y_L^{\frac{\sigma-1}{\sigma}} + (1-\gamma) Y_E^{\frac{\sigma-1}{\sigma}} \right]^{\frac{1}{\sigma-1}} \gamma Y_L^{-\frac{1}{\sigma}}, \tag{A.6.2}$$

$$p_{YE} = p_Y \left[\gamma Y_L^{\frac{\sigma-1}{\sigma}} + (1-\gamma) Y_E^{\frac{\sigma-1}{\sigma}} \right]^{\frac{1}{\sigma-1}} (1-\gamma) Y_E^{-\frac{1}{\sigma}}. \tag{A.6.3}$$

Dividing both expressions gives (6.2). Combining (6.1) with (A.6.2)-(A.6.3), we get:

$$p_Y Y = p_{YL} Y_L + p_{YE} Y_E. \tag{A.6.4}$$

Substitution of (A.6.2)-(A.6.3) into the production function (6.1) and combining the result with (A.6.4), we obtain an expression for the price index of final output:

$$p_Y = [\gamma(1-\gamma)]^{-1} \left\{ \gamma \left[(1-\gamma) p_{YL}\right]^{1-\sigma} + (1-\gamma) \left[\gamma p_{YE}\right]^{1-\sigma} \right\}^{\frac{1}{1-\sigma}}. \tag{A.6.5}$$

6.A.2 Intermediate Goods

The Hamiltonian associated with the optimization problem of firm k in the intermediate good sector is given by:

$$\mathcal{H}_{ik} = p_{Yi}(1-\beta) q_{ik} S_i^{\beta} x_{ik}^{1-\beta} - q_{ik} p_Y x_{ik} - w_D D_{ik} + \lambda_{ik} \xi_i Q_i D_i, \tag{A.6.6}$$

where $i = S_i = \{R, L\}$. The necessary first-order conditions for an optimum are given by:

$$\frac{\partial \mathcal{H}_{ik}}{\partial x_{ik}} = 0 \Rightarrow (1-\beta)^2 p_{Yi} q_{ik} S_i^{\beta} x_{ik}^{-\beta} = q_{ik} p_Y, \tag{A.6.7}$$

$$\frac{\partial \mathcal{H}_{ik}}{\partial D_{ik}} \leqslant 0 \Rightarrow -w_D + \lambda_{ik}\xi_i Q_i \leqslant 0, \quad \text{with equality if} \quad D_{ik} > 0, \tag{A.6.8}$$

$$\frac{\partial \mathcal{H}_{ik}}{\partial q_{ik}} = -\dot{\lambda}_{ik} + r\lambda_{ik} \Rightarrow p_{Yi}(1-\beta) S_i^{\beta} x_{ik}^{1-\beta} - x_{ik} p_Y = -\dot{\lambda}_{ik} + r\lambda_{ik}. \tag{A.6.9}$$

The transversality conditions are given by (6.13)-(6.14). Substitution of (6.8) in (A.6.7) gives (6.10a), (A.6.8) directly implies (6.10b), and the combination of (A.6.7) and (A.6.9) gives (6.10c). Combining (6.8) with (6.10a), we obtain:

$$x_{ik} = x_i = \left(\frac{p_{Yi}(1-\beta)^2}{p_Y}\right)^{\frac{1}{\beta}} S_i = \frac{\theta_i Y (1-\beta)^2}{Q_i}. \tag{A.6.10}$$

where the second equality uses (6.5) and (6.15).

6.A.3 Households

The wealth of households is equal to

$$V = w_R S + \lambda_L Q_L + \lambda_R Q_R, \tag{A.6.11}$$

so that the change in wealth over time equals:

$$\dot{V} = \dot{w_R} S - w_R R + \dot{\lambda}_L Q_L + \lambda_L \dot{Q}_L + \dot{\lambda}_R Q_R + \lambda_R \dot{Q}_R, \tag{A.6.12}$$

where we have used (6.6) to substitute for $\dot{S}$. Defining π_i as profits per unit of quality, total profits in each intermediate goods sector are equal to $Q_i \pi_i = p_{xi} x_i - p_Y Q_i$, so that (6.10a) and (6.10c) can be combined to get

$$p_{xi} x_i = Q_i r \lambda_i - Q_i \dot{\lambda}_i + Q_i x_i. \tag{A.6.13}$$

Combining (A.6.4), (6.4), (6.5), and (6.7)-(6.8) we obtain:

$$p_Y Y = w_L L + p_{xL} x_L + w_R R + p_{xR} x_R + \eta H. \tag{A.6.14}$$

Plugging (A.6.13) in (A.6.14) and using the resulting expression to substitute for $w_R R$ in (A.6.12), we get:

$$\dot{V} = p_Y Y - Q_L x_L - Q_R x_R - \eta H + w_L L + r Q_L \lambda_L + r Q_R \lambda_R + \lambda_L \dot{Q}_L + \lambda_R \dot{Q}_R. \tag{A.6.15}$$

By combining (6.26) and (A.6.8) we obtain $\lambda_i \dot{Q}_i = \lambda_i \xi_i Q_i D_i = w_D D_i$. Using this expression together the market equilibrium conditions from Section 6.2.2 in (A.6.15), we obtain the flow budget constraint of the households (6.19).

The Hamiltonian associated with the optimization problem of the households reads:

$$\mathcal{H} = \ln(C) + \lambda_V \left[r(V - w_R S) + \dot{w}_R S + w L^S - p_C C \right]. \tag{A.6.16}$$

The necessary first-order conditions for an optimum are given by:

$$\frac{\partial \mathcal{H}}{\partial C} = 0 \Rightarrow \frac{1}{C} - \lambda_V p_C = 0 \Rightarrow \hat{C} + \hat{p}_C = -\hat{\lambda}_V, \tag{A.6.17}$$

$$\frac{\partial \mathcal{H}}{\partial S} = 0 \Rightarrow -\lambda_V r w_R + \lambda_V \dot{w}_R = 0 \Rightarrow \hat{p}_R = r, \tag{A.6.18}$$

$$\frac{\partial \mathcal{H}}{\partial V} = -\dot{\lambda}_V + \rho \lambda_V \Rightarrow \lambda_V r = -\dot{\lambda}_V + \rho \lambda_V. \tag{A.6.19}$$

The transversality condition is given by (6.20). Combining (A.6.17) and (A.6.19) gives the Ramsey rule (6.21). The first-order condition (A.6.18) is the Hotelling rule (6.22).

6.A.4 Income Shares

This section derives the income shares for $t < T_{23}^{+}$, when $\omega_H = Y_H = 0$ so that $\theta_E = \theta_R$. We substitute (6.5) into (6.2) and use (A.6.10) to get

$$\frac{p_{YR}}{p_{YL}} = \frac{1-\gamma}{\gamma} \left(\frac{Y_R}{Y_L} \right)^{-\frac{1}{\sigma}} = \left(\frac{p_{YR}}{p_{YL}} \right)^{\frac{1}{\beta}} \frac{R Q_R}{L Q_L} = \left(\frac{1-\gamma}{\gamma} \right)^{\frac{\beta\sigma}{\nu}} \left(\frac{R Q_R}{L Q_L} \right)^{-\frac{\beta}{\nu}}. \tag{A.6.20}$$

Using the income share definition (6.15) together with (A.6.20), we find

$$\frac{\theta_R}{1-\theta_R} = \left(\frac{1-\gamma}{\gamma} \right)^{\frac{\sigma}{\nu}} \left(\frac{R Q_R}{L Q_L} \right)^{\frac{\nu-1}{\nu}} = \left(\frac{w_R}{w_L} \frac{Q_L}{Q_R} \right)^{1-\nu} \left(\frac{1-\gamma}{\gamma} \right)^{\sigma}, \tag{A.6.21}$$

where the second equality additionally uses (6.7) and (A.6.10) to obtain the price ratio

$$\begin{aligned} \frac{w_R}{w_L} &= \frac{p_{YR}}{p_{YL}} \left(\frac{R}{L} \right)^{\beta-1} \frac{Q_R}{Q_L} \left(\frac{x_R}{x_L} \right)^{1-\beta} = \left(\frac{p_{YR}}{p_{YL}} \right)^{\frac{1}{\beta}} \frac{Q_R}{Q_L} \\ &= \left(\frac{1-\gamma}{\gamma} \right)^{\frac{\sigma}{\nu}} \left(\frac{R}{L} \right)^{-\frac{1}{\nu}} \left(\frac{Q_R}{Q_L} \right)^{\frac{\nu-1}{\nu}}. \end{aligned} \tag{A.6.22}$$

6.A.5 Real Interest Rate

If we combine (6.5) with (6.7), and (6.8) to find the price index p_{YL} and subsequently convert the expression into growth rates, we get

$$\hat{p}_{YL} = \beta\hat{w}_L + (1-\beta)(\hat{Q}_L + \hat{p}_Y) - \hat{Q}_L. \tag{A.6.23}$$

Converting the price index (A.6.5) into growth rates and using (A.6.2)-(A.6.3), we obtain

$$\hat{p}_Y = \theta_E\hat{p}_{YE} + (1-\theta_E)\hat{p}_{YL}. \tag{A.6.24}$$

Combining (A.6.23) and (A.6.24), and using (A.6.22), we find an expression for the real rate of interest:

$$r - \hat{p}_Y = r - \hat{w}_L - (\hat{p}_Y - \hat{w}_D) = (1-\theta_E)\left[r - \hat{w}_D - (\hat{Q}_R - \hat{Q}_L)\right] + \hat{Q}_R. \tag{A.6.25}$$

The second equalities in (6.30) and (6.33c) follow from the combination of (A.6.25) with the first equalities in (6.30) and (6.33c).

6.A.6 Research and Income Share Isoclines Regime 1

This section derives some relevant properties of the research and income share isoclines in regime 1.

6.A.6.1 Properties and First-Order Derivatives

By imposing the steady state (i.e. $\dot{\theta}_E = \dot{D} = 0$ in the dynamic system (6.31a)-(6.31b) we find the following isoclines:

$$D|_{\dot{\theta}_E=0} = \frac{L^S(1-\beta)\left[\xi_L(\xi_L+2\xi_R) - \theta(\xi_L+\xi_R)^2\right]}{\xi_L^2(1-\beta)(1-\theta_E) + \xi_L\xi_R(3-2\beta)(1-\theta_E) - \xi_R^2(1-\beta)\theta_E}, \tag{A.6.26}$$

$$D|_{\dot{D}=0} = \frac{\Xi}{\Omega}, \tag{A.6.27}$$

where

$$\begin{aligned}
\Xi \equiv\ & L^S(1-\beta)\left[\xi_L\xi_R - (1-\nu)\xi_L(\xi_L+2\xi_R)\theta_E + (1-\nu)(\xi_L+\xi_R)^2\theta_E^2\right] \\
& - (\xi_L+\xi_R)(1-\theta_E)\rho, \\
\Omega \equiv\ & (1-\nu)(1-\beta)\xi_R^2\theta_E^2 - (1-\nu)\xi_L^2(1-\beta)(1-\theta_E)\theta_E \\
& + \xi_L\xi_R\left[2 - \theta_E(4 - 3\nu(1-\theta_E) - 3\theta_E) - \beta(1 - 2(1-\nu)(1-\theta_E)\theta_E)\right].
\end{aligned}$$

It follows from the denominator of (A.6.26) that the $\dot{\theta}_E = 0$ isocline has a vertical asymptote at:

$$\theta_E^A \equiv \frac{\xi_L[\xi_L(1-\beta) + \xi_R(3-2\beta)]}{(1-\beta)(\xi_L+\xi_R)^2 + \xi_L\xi_R} > 0. \tag{A.6.28}$$

The intersection point of the two isoclines, (θ_E^*, D^*) satisfies:

$$\theta_E^* = \frac{\xi_L\left\{L^S\xi_L\xi_R(1-\beta) + [\xi_L(1-\beta)+\xi_R(3-2\beta)]\,\rho\right\}}{L^S\xi_L\xi_R(\xi_L+\xi_R)(1-\beta) + [\xi_L^2+\xi_R^2+3\xi_L\xi_R-(\xi_L+\xi_R)^2\beta]\,\rho} > 0, \tag{A.6.29}$$

$$D^* = \frac{L^S\xi_L(\xi_L+\xi_R)(1-\beta) - \xi_R\rho}{\xi_L\,[\xi_R(2-\beta)+\xi_L(1-\beta)]}. \tag{A.6.30}$$

The corner properties for the two isoclines are:

$$D|_{\dot{\theta}_E=0,\theta_E=0} = L^S - \frac{L^S\xi_R}{\xi_L(1-\beta)+\xi_R(3-2\beta)}, \tag{A.6.31}$$

$$D|_{\dot{D}=0,\theta_E=0} = \frac{L^S\xi_L\xi_R(1-\beta) - (\xi_L+\xi_R)\rho}{\xi_L\xi_R(2-\beta)}, \tag{A.6.32}$$

$$D|_{\dot{\theta}_E=0,\theta_E=1} = D|_{\dot{D}=0,\theta_E=1} = L^S. \tag{A.6.33}$$

The first-order derivative of the income share isocline with respect to θ_E is given by:

$$\frac{d(D|_{\dot{\theta}_E=0})}{d\theta_E} = -\frac{L^S\xi_L\xi_R^3(1-\beta)}{[\xi_L(1-\beta)(1-\theta_E)+\xi_L\xi_R(3-2\beta)(1-\theta_E)-\xi_R^2(1-\beta)\theta_E]^2} < 0.$$

The first-order derivative of the research isocline with respect to θ_E at $\theta_E = 1$ is given by:

$$\left.\frac{d(D|_{\dot{D}=0})}{d\theta_E}\right|_{\theta_E=1} = \frac{(\xi_L+\xi_R)\rho + L^S\xi_L\xi_R[1-\beta(1-\sigma)]}{\xi_R(1-\beta)[\xi_L+\xi_R\beta(1-\sigma)]} > 0. \tag{A.6.34}$$

The first-order derivative of the research isocline with respect to θ_E at $\theta_E = 0$ is given by:

$$\left.\frac{d(D|_{\dot{D}=0})}{d\theta_E}\right|_{\theta_E=0} = \frac{\Gamma}{\Lambda}, \tag{A.6.35}$$

where

$$\begin{aligned}\Gamma \equiv\ & L^S\xi_L\xi_R(1-\beta)\,[\xi_R[1-\beta(1-\sigma)] - \xi_L\beta(1-\sigma)] \\ & + (\xi_L+\xi_R)\rho\,[\xi_R(1-\beta(4-2\beta(1-\sigma)+3\sigma)) - \xi_L(1-\beta)\beta(1-\sigma)]\,, \\ \Lambda \equiv\ & \xi_L\xi_R^2(2-\beta)^2 > 0.\end{aligned}$$

Hence, the sign of (A.6.35) depends on the parameter values. However, it can be shown that $\Gamma < 0$ if ξ_R is small relative to ξ_L, e.g. if $\xi_R = 0$, we obtain:

$$\Gamma|_{\xi_L=0} = -\xi_L(1-\beta)\beta\rho(1-\sigma) < 0, \tag{A.6.36}$$

so that the first-order derivative of the research isocline with respect to θ_E is negative at $\theta_E = 0$ if ξ_R is relatively small.

6.A.6.2 Relative Positions

At $\theta_E = 0$, the difference between the income share isocline and the research isocline is given by:

$$(D|_{\dot{\theta}_E=0} - D|_{\dot{D}=0})|_{\theta_E=0} = \frac{\xi_L + \xi_R}{2-\beta}\left(\frac{\rho}{\xi_L\xi_R} + \frac{L^S(1-\beta)}{\xi_L(1-\beta)+\xi_R(3-2\beta)}\right) > 0.$$

Because $D|_{\dot{D}=0,\theta_E=1} = L^S$ and $\lim_{\theta_E \to \theta_E^A} D|_{\dot{\theta}_E=0} = -\infty$, the two isoclines cross exactly once and the intersection point is located to the left of the vertical asymptote of the research isocline.

6.A.7 Extraction Isocline Regime 1

This section derives some relevant properties of the extraction isocline in regime 1.

6.A.7.1 Properties and First-Order Derivative

Substitution of (6.17), (6.27) and (6.28) into (6.30) and imposing $\dot{R} = 0$, we obtain the extraction isocline, which also has a vertical asymptote at θ_E^A:

$$D|_{\dot{R}=0} = -\frac{(\xi_L+\xi_R)\rho + L^S(1-\beta)\beta(1-\sigma)[(\xi_L+\xi_R)^2\theta_E - \xi_L(\xi_L+2\xi_R)]}{\beta(1-\sigma)[\xi_L^2(1-\beta)(1-\theta_E) + \xi_L\xi_R(3-2\beta)(1-\theta_E) - \xi_R^2(1-\beta)\theta_E]}.$$

The first-order derivative of the extraction isocline with respect to θ_E is given by:

$$\frac{d(D|_{\dot{R}=0})}{d\theta_E} = -\frac{(\xi_L+\xi_R)\left[(\xi_L^2+\xi_R^2)(1-\beta)+\xi_L\xi_R(3-2\beta)\right]\rho + L^S\xi_L\xi_R^3(1-\beta)\beta(1-\sigma)}{\beta[\xi_L^2(1-\beta)(1-\theta_E)+\xi_L\xi_R(3-2\beta)(1-\theta_E)-\xi_R^2(1-\beta)\theta_E](1-\sigma)}.$$

Hence, $d(D|_{\dot{R}=0})/d\theta_E < 0$ if $\theta_E < \theta_E^A$.

6.A.7.2 Relative Position

The difference between the income share isocline and the extraction isocline is given by:

$$D|_{\dot{\theta}_E=0} - D|_{\dot{R}=0} = \frac{(\xi_L + \xi_R)\rho(1-\sigma)^{-1}}{\beta[\xi_L^2(1-\beta)(1-\theta_E) + \xi_L\xi_R(3-2\beta)(1-\theta_E) - \xi_R^2(1-\beta)\theta_E]}.$$

It follows that $D|_{\dot{\theta}_E=0} - D|_{\dot{R}=0} > 0$ and $\lim_{\sigma\to 1}[D|_{\dot{\theta}_E=0} - D|_{\dot{R}=0}] = \infty$ if $\theta_E < \theta_E^A$.

6.A.8 First-Order Derivatives of Differential Equations in Regime 1

The first-order derivative of the differential equation for θ_E with respect to D is given by:

$$\frac{d\dot{\theta}_E}{dD} = -\frac{\beta\theta_E[\xi_L^2(1-\beta)(1-\theta_E) + \xi_L\xi_R(3-2\beta)(1-\theta_E) - \xi_R^2(1-\beta)\theta_E](1-\sigma)}{(\xi_L + \xi_R)}.$$

Therefore, $d\dot{\theta}_E/dD < 0$ if $\theta_E < \theta_E^A$. The first-order derivative of the differential equation for D with respect to D for combinations of θ_E and D along the D-isocline is given by:

$$\left.\frac{d\dot{D}}{dD}\right|_{\dot{D}=0} = \frac{(\xi_L + \xi_R)\rho + L^S\xi_L\xi_R\left[1 - \beta\theta_E(1-\sigma)\right]}{\xi_L + \xi_R} > 0. \tag{A.6.37}$$

Hence, $d\dot{D}/dD > 0$ in the neighborhood of the research isocline in (θ_E, D)-space. The first-order derivative of the differential equation for R with respect to D is given by:

$$\frac{d\dot{R}}{dD} = -\frac{\beta R[\xi_L^2(1-\beta)(1-\theta_E) + \xi_L\xi_R(3-2\beta)(1-\theta_E) - \xi_R^2(1-\beta)\theta_E](1-\sigma)}{(\xi_L + \xi_R)}.$$

Therefore, $d\dot{R}/dD < 0$ if $\theta_E < \theta_E^A$.

6.A.9 Research and Income Share Isoclines Regime 2

This section derives some relevant properties of the research and income share isoclines in regime 2.

6.A.9.1 Properties and First-Order Derivatives

By imposing the steady state (i.e. $\dot{\theta}_E = \dot{D} = 0$) in the dynamic system (6.34a)-(6.34b) we find the following isoclines:

$$D|_{\dot{\theta}_E=0} = L^S, \tag{A.6.38}$$

$$D|_{\dot{D}=0} = L^S - \frac{L^S\xi_L + \rho}{\xi_L\left[2-\beta(1-(1-\beta)\theta_E(1-\sigma))\right]}. \tag{A.6.39}$$

The corner properties for the two isoclines are:

$$D|_{\dot{\theta}_E=0,\theta_E=0} = D|_{\dot{\theta}_E=0,\theta_E=1} = L^S \tag{A.6.40}$$

$$D|_{\dot{D}=0,\theta_E=0} = L^S - \frac{L^S\xi_L + \rho}{\xi_L(2-\beta)}, \tag{A.6.41}$$

$$D|_{\dot{D}=0,\theta_E=1} = L^S - \frac{L^S\xi_L + \rho}{\xi_L\left[2-\beta[1+(1-\beta)(1-\sigma)]\right]}. \tag{A.6.42}$$

The first-order derivative of the income share isocline with respect to θ_E equals zero. The first-order derivative of the research isocline with respect to θ_E is given by:

$$\frac{d(D|_{\dot{\theta}_E=0})}{d\theta_E} = -\frac{(1-\beta)(1-\sigma)\beta(L^S\xi_L + \rho)}{\xi_L\left[2-\beta(1+(1-\beta)\theta_E(1-\sigma))\right]^2} < 0. \tag{A.6.43}$$

6.A.9.2 Relative Positions

Comparing (A.6.38) and (A.6.39), we find that $D|_{\dot{\theta}_E=0} > D|_{\dot{D}=0}$.

6.A.10 Extraction Isocline Regime 1

This section derives some relevant properties of the extraction isocline in regime 1.

6.A.10.1 Properties and First-Order Derivative

Substitution of (6.17), (6.32) and (6.33a) into (6.33c) and imposing $\dot{R} = 0$, we obtain the extraction isocline

$$D|_{\dot{R}=0} = L^S - \frac{\rho}{\xi_L\beta(1-\beta)(1-\theta_E)(1-\sigma)}. \tag{A.6.44}$$

The first-order derivative of the extraction isocline with respect to θ_E is given by:

$$\frac{d(D|_{\dot{R}=0})}{d\theta_E} = -\frac{\rho}{\xi_L(1-\beta)(1-\sigma)\beta(1-\theta_E)^2} < 0. \tag{A.6.45}$$

We have the following corner properties for (A.6.44):

$$\lim_{\theta_E \to 1} D|_{\dot{R}=0} = -\infty, \tag{A.6.46}$$

$$D|_{\dot{R}=0,\theta_E=0} < D|_{\dot{\theta}_E=0}. \tag{A.6.47}$$

It follows that the extraction isocline is located below the income share isocline in (θ_E, D)-space, i.e. $D|_{\dot{R}=0} < D|_{\dot{\theta}_E=0}$.

6.A.11 First-Order Derivatives of Differential Equations in Regime 2

The first-order derivative of the differential equation for θ_E with respect to D is given by:

$$\frac{d\dot{\theta}_E}{dD} = -\xi_L(1-\beta)(1-\theta_E)(1-\sigma)\beta\theta_E < 0. \tag{A.6.48}$$

The first-order derivative of the differential equation for D with respect to D for combinations of θ_E and D along the D-isocline is given by:

$$\left.\frac{d\dot{D}}{dD}\right|_{\dot{D}=0} = L^s\xi_L + \rho > 0. \tag{A.6.49}$$

Hence, $d\dot{D}/dD > 0$ in the neighborhood of the research isocline in (θ_E, D)-space. The first-order derivative of the differential equation for R with respect to D is given by:

$$\frac{d\dot{R}}{dD} = -\xi_L(1-\beta)(1-\theta_E)(1-\sigma)\beta R < 0. \tag{A.6.50}$$

6.A.12 Exclusion of Simultaneous Use

We show that it is not possible to have a regime of simultaneous use of the resource and the backstop technology. Simultaneous use requires equal effective prices of the resource and the backstop technology, so that $p_{YH} = p_{YR} = p_{YE}$. Using $p_{YH} = p_Y/\eta$, this implies

$$\hat{p}_Y = \hat{p}_{YH} = \hat{p}_{YR} = \hat{p}_{YE}. \tag{A.6.51}$$

If we combine (6.5) with (6.7), and (6.8) to find the price indexes p_{YL} and p_{YR}, and subsequently convert the expression into growth rates, we get

$$\hat{p}_{YL} - \hat{p}_Y = \beta(\hat{w}_L - \hat{p}_Y - \hat{Q}_L), \tag{A.6.52}$$

$$\hat{p}_{YR} - \hat{p}_Y = \beta(\hat{w}_R - \hat{p}_Y - \hat{Q}_R). \tag{A.6.53}$$

Using (A.6.24) together with (A.6.51), we find $\hat{p}_{YL} = \hat{p}_Y$. Substitution of this result into (A.6.52) and (A.6.51) into (A.6.53), and using the Ramsey rule (6.21), we obtain

$$r - \hat{w_D} = \hat{Q}_R - \hat{Q}_L \tag{A.6.54}$$

Substitution of (6.17) into (6.12), in a regime with purely labor-augmenting technical change (i.e. $\hat{Q}_L > 0$ and $\hat{Q}_R = 0$) we have

$$r - \hat{w_D} = (1-\beta)\xi_L(L^S - D) - \hat{Q}_L. \tag{A.6.55}$$

The conditions (A.6.54) and (A.6.55) can only be satisfied jointly if $D = L^S$. However, this implies that $L = Y = 0$, which cannot hold in equilibrium because it implies $\hat{C} = \hat{Y} = 0$, whereas the Ramsey rule (6.21) together with (A.6.53) gives $\hat{C} = -\rho$. Hence, during a regime with purely labor-augmenting technical change, the effective relative price of the resource and the backstop cannot be constant, so that simultaneous use of both energy sources will not occur. As a result, simultaneous use is also impossible in a regime with both resource-augmenting and labor-augmenting technical change. Optimality condition (6.10b) together with (6.14) namely implies that the economy eventually necessarily shifts to a regime without resource-augmenting technical change. Condition (6.39) requires that θ_E is continuous at this regime shift. However, the beginning of the regime without resource-augmenting technical change, $\theta_E < (1-\gamma)^\sigma \eta^{\sigma-1}$.[16] The jump from a regime with simultaneous use with resource-augmenting and labor-augmenting technical change to a regime with purely labor-augmenting technical change necessarily implies a discontinuity in θ_E. Therefore, a regime of simultaneous use cannot exist.

6.A.13 Proof Downward Jump in D_R

We proof the downward dump in D_R by contradiction. Suppose that $D^-_{R12} = D^+_{R12} \Rightarrow \hat{Q}^-_{R12} = \hat{Q}^+_{R12}$. From (6.10b), we get $\hat{\mu}^-_{12} = 0$. The end condition $\mu^+_{23} = 0$

[16] This inequality follows from the continuity of μ, optimality condition (6.10b), and (6.34a).

in (6.48b) and the differential equation for μ, (6.50), imply that $\hat{\mu}_{12}^{+} < 0$. Using definition (6.46), we obtain

$$(\hat{\lambda}_R - \hat{w}_D)_{12}^{-} > (\hat{\lambda}_R - \hat{w}_D)_{12}^{+}. \tag{A.6.56}$$

Rearranging optimality condition (6.10c), we get

$$r - \hat{w}_D = \frac{\beta}{1-\beta} \frac{\theta_R p_Y Y (1-\beta)^2}{Q_R \lambda_R} + \hat{\lambda}_R - \hat{w}_D. \tag{A.6.57}$$

Combining (A.6.56) and (A.6.57), and using the continuity of Q_R, Y, λ_R, and θ_R, we find $(r - \hat{w}_D)_{12}^{-} > (r - \hat{w}_D)_{12}^{+}$. Substitution of this result into (6.12) with $i = L$ implies $\hat{Q}_{L12}^{-} > \hat{Q}_{L12}^{+} \Rightarrow D_{L12}^{-} > D_{L12}^{+}$. Using the continuity of D at T_{12} and the identity $D = D_L + D_R$, we obtain $D_{R12}^{-} > D_{R12}^{+}$. This contradicts our initial assumption of a continuous D_R at T_{12}. Hence, D_R jumps down at the end of regime 1. □

6.A.14 Initial Condition

By combining (6.5) with (6.23) and using the definition $y \equiv S/R$, the relative factor demand function can be written as:

$$\frac{\theta_E}{1-\theta_E} \left(\frac{1-\gamma}{\gamma}\right)^{\frac{\sigma}{\nu}} \left(\frac{S}{y(L^S - D)} \frac{Q_R}{Q_L}\right)^{\frac{\nu-1}{\nu}}. \tag{A.6.58}$$

Converting (A.6.58) into growth rates, we find:

$$\hat{\theta}_E = -(1-\theta_E)\frac{1-\nu}{\nu}\left[\hat{S} - \hat{y} + \frac{D}{L^S - D}\hat{D} + \hat{Q}_R - \hat{Q}_L\right]. \tag{A.6.59}$$

By using (6.17), (6.24), and $\hat{S} = -y^{-1}$, we get a differential equation for y:

$$\dot{y} = -y(1-\nu)(1-\theta_E)\left[r - \hat{w}_L - (\hat{Q}_R - \hat{Q}_L)\right] + \rho y - 1. \tag{A.6.60}$$

For each regime, the specification of the differential equation in terms of y, θ_E, and D is different. Substitution of (6.17), (6.27), and (6.28) into (A.6.60) gives (6.51a), the required differential equation for y in regime 1. By instead substituting $\hat{Q}_R = 0$, (6.32) and (6.33a), and using (6.17) again, we obtain (6.51b), the required differential equation in regime 2. Expression (6.52) is obtained by substitution of S_0, $Q_R(0)$, $Q_L(0)$ and the function $D = f(\theta_E)$ into (A.6.58).

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Samenvatting

De analyse in dit proefschrift maakt gebruik van dynamische algemene evenwichtstheorie teneinde twee verschillende onderwerpen binnen de economische wetenschap te bestuderen. Het eerste deel (hoofdstuk 2 en 3) gaat over de effecten van handelsliberalisering op de allocatie van middelen en op de welvaart in kleine open ontwikkelingseconomieën. Het tweede deel (hoofdstuk 4, 5, en 6) is gewijd aan het bestuderen van de transitie in energiegebruik van het verbranden van fossiele brandstoffen naar het opwekken van energie met alternatieve technologieën in de wereldeconomie. Behoudens de inhoudelijke verschillen, vertonen beide delen van het proefschrift op methodologisch vlak een sterke verwantschap. Ten eerste benaderen alle hoofdstukken de verschillende problemen vanuit een macroeconomisch algemeen evenwichtsperspectief, terwijl micro-economische partiële analyses de bestaande literatuur domineren. Daarenboven wordt voortdurend in plaats van het bepalen van de allocatie van schaarse middelen die een welwillende sociale ingenieur zou voorstaan, een gedecentraliseerd marktevenwicht in imperfecte economieën als uitgangspunt genomen. In het vervolg van deze samenvatting worden, na een korte introductie van beide onderzoeksgebieden, de belangrijkste conclusies van dit proefschrift over het voetlicht gebracht.

Handelsliberalisering in ontwikkelingslanden

Inleiding

Een van de 'tien geboden' waaruit de zogenoemde Washington Consensus van 1990 bestaat, verordineert dat de door de schuldencrisis tijdens het 'verloren decennium' getroffen Latijns-Amerikaanse landen hun handel moeten liberaliseren met het oogmerk economische groei, ontwikkeling en armoedereductie te bevorderen (zie Williamson, 2000). Handelsliberalisering werd daarom een standaard onderdeel van de structurele hervormingsprogramma's van het Internationaal Monetair Fonds (IMF) en de Wereldbank. Ten gevolge hiervan zagen veel ontwikkelingslanden zich gedwongen om handelsbarrières, met name in de vorm van tarieven op internationale handel, te verminderen. Naast het beschermen van binnenlandse industrieën, zijn deze handelsbelastingen echter ook een een belangrijke bron van inkomsten voor overheden in ontwikkelingslanden (zie Ebrill, Stotsky, en Gropp, 1999; Dalsgaard, 2005; Baunsgaard en Keen, 2010). Tijdens het afgelopen decennium bestonden de totale belastinginkomsten van lage inkomenslanden voor 29 procent uit belastingen op internationale handel, terwijl ditzelfde aandeel in OESO landen minder was dan 1 procent (Wereldbank, 2012).[1]

Met het oog op de relatief sterke afhankelijkheid van handelsbelastingen en de vaak precaire budgettaire situatie van overheden in ontwikkelingslanden, pleitten het IMF en de Wereldbank herhaaldelijk voor een gecoördineerde belastingtariefhervorming bestaande uit het verlagen van invoertarieven, tezamen met een verhoging van binnenlandse belastingtarieven teneinde aantasting van de overheidsinkomsten te voorkomen. Meestal wordt een belasting op de toegevoegde waarde (BTW) genoemd als geprefereerd instrument om de binnenlandse belastingopbrengst te verhogen (Emran en Stiglitz, 2005). Deze strategie van het verlagen van invoertarieven, gekoppeld met het verhogen of invoeren van BTW tarieven is inmiddels op grote schaal geïmplementeerd in ontwikkelingseconomieën. Het aantal lage inkomenslanden met een BTW systeem is toegenomen van 8 tot 26 tussen 1990 en 2010. Tijdens dezelfde periode is in deze landen het gecollecteerde invoertarief gedaald van 20 tot 10 procent (Baunsgaard en Keen, 2010).[2]

Bijdrage en bevindingen

De theoretische onderbouwing van het beleidsadvies der vanuit Washington D.C. opererende instituties is gebaseerd op de welvaartswinsten die de voorgestane hervormingen genereren in eenvoudige modellen van kleine open economieën. Hatzipanayotou, Michael, en Miller (1994) alsmede Keen en Ligthart (2002) hebben aangetoond dat een gecoördineerde belasting-tariefhervorming bestaande uit het

[1] De groep lage inkomenslanden is gedefinieerd volgens de huidige Wereldbank classificatie (Wereldbank, 2012).

[2] Het gecollecteerde invoertarief is gedefinieerd als de totale waarde van overheidsinkomsten uit invoertarieven gedeeld door de totale waarde van de invoer.

verlagen van invoertarieven in combinatie met een verhoging van de consumptiebelasting op een zodanige wijze dat de consumentenprijzen ongewijzigd blijven, leidt tot een toename van zowel de welvaart als de overheidsinkomsten. De reden voor deze veelbelovende bevinding is dat het verlagen van invoertarieven leidt tot een efficiëntere productiestructuur, terwijl het verlies aan overheidsinkomsten meer dan gecompenseerd wordt door de verhoging van de consumptiebelastingtarieven, omdat de grondslag voor de consumptiebelasting groter is dan die van het invoertarief.

Het basismodel voor de analyse van de hervormingseffecten is vervolgens in verschillende richtingen uitgebreid door Haque en Mukherjee (2005), Emran en Stiglitz (2005), Keen en Ligthart (2005), Anderson en Neary (2007), Kreickemeier en Raimondos-Moller (2008), Munk (2008), en Davies en Paz (2011). Hoewel de bestaande literatuur op het gebied dus omvangrijk is, wordt er in de huidige analyses veelvuldig gebruik gemaakt van statische (partiële) evenwichtsmodellen waarin het aanbod van productiefactoren exogeen en constant is.[3] Dientengevolge worden dynamische effecten op de werkgelegenheid en de accumulatie van kapitaal genegeerd. Aangezien Brock en Turnovsky (1993) hebben aangetoond dat de reactie van de kapitaalgoederenvoorraad van belang is voor de effecten van veranderingen in invoertarieven, leidt het abstraheren hiervan tot vertekende resultaten.

Het onderhavige proefschrift probeert dit hiaat in de literatuur over gecoördineerde handelsliberalisering op te vullen, door een dynamisch algemeen evenwichtsmodel van een kleine open economie te construeren. Voortbouwend op Brock en Turnovsky (1993), veronderstelt de analyse dat agenten vooruitkijkend zijn en rationele verwachtingen hebben. In het model van hoofdstuk 2 ontlenen huishoudens zowel nut aan consumptie als aan vrije tijd, waardoor het arbeidsaanbod endogeen bepaald wordt. De productiestructuur is zodanig gekozen dat deze *grosso modo* in overeenstemming is met die van een 'doorsnee ontwikkelingsland': de aanbodzijde bestaat uit een agrarische export sector en een industriële sector die moet concurreren met de invoer van industriële goederen. Voorts wordt aangenomen dat kapitaalgoederen niet binnenslands worden geproduceerd, maar ingevoerd worden uit het buitenland. Fysiek kapitaal wordt louter gebruikt in de industriële sector, terwijl de productiefactor land slechts benodigd is voor de productie van het agrarische goed. Arbeid wordt ingezet in beide sectoren en kan vrij bewegen tussen de agrarische en industriële sector. De overheid kan niet

[3]Naito (2003; 2006a; 2006b), Portes (2009) en Atolia (2010) zijn noemenswaardige uitzonderingen.

beschikken over lump-sum belastingen moet voor het genereren van een exogeen bepaalde hoeveelheid inkomsten derhalve haar toevlucht nemen tot het heffen van verstoringen belastingen op consumptie en looninkomen, en tarieven op ingevoerde kapitaal- consumptiegoederen. Het beschreven model wordt gebruikt om, gegeven de bestaande structuur van belastingen en invoertarieven, de effecten van een geïntegreerde belasting-invoertariefhervormingen in kaart te brengen. *In conreto* bestaat de hervorming uit het verlagen van het tarief op ingevoerde consumptiegoederen, tezamen met een zodanige aanpassing van de consumptiebelasting dat de overheidsinkomsten op ieder moment onveranderd blijven.

De hervorming leidt tot een toename van de geaggregeerde productie op korte termijn, als gevolg van een efficiëntere allocatie van arbeid over de twee productiesectoren en een toename van het arbeidsaanbod. Hoewel de agrarische productie ook op lange termijn hoger blijft, zijn zowel de geaggregeerde productie als de werkgelegenheid in het nieuwe stationaire evenwicht lager dan voor de hervorming het geval was, ten gevolge van een afname van de kapitaalgoederenvoorraad in de industriële sector. Voor wat betreft de welvaartseffecten zijn vier bevindingen van belang. Ten eerste stijgt de welvaart onder plausibele omstandigheden, omdat—startend vanuit de initiële belasting- en tariefstructuur—de vermindering van de verstoring van het invoertarief (resulterend in teveel productie en te weinig consumptie van het industriële goed) zwaarder weegt dan de stijging van de verstoring van de consumptiebelasting (resulterend in een te laag arbeidsaanbod). Een belangrijke drijfveer van dit resultaat is dat tarieven in een dynamisch raamwerk niet louter de contemporaine allocatie van consumptie en productiefactoren verstoren, maar daarenboven van invloed zijn op de investeringsbeslissing van bedrijven in de industriële sector. Ten tweede volgt uit de analyse dat de endogene reactie van het arbeidsaanbod het welvaartseffect negatief beïnvloedt. De reden is dat intertemporele substitutie van arbeid ertoe leidt dat het arbeidsaanbod initieel stijgt en op lange termijn daalt. Ten derde wijzen de resultaten erop dat het welvaartseffect positief afhangt van de substitutie-elasticiteiten tussen de productiefactoren. Ten slotte blijkt dat een hogere kapitaalmobiliteit de dynamische component van het welvaartseffect versterkt.

Hoofdstuk 3 brengt het analytische raamwerk meer in overeenstemming met de realiteit in ontwikkelingslanden, door een informele sector of zwarte markt die niet belast kan worden te introduceren. Schneider en Enste (2000) rapporteren omvangrijke informele sectoren in lage inkomenslanden, variërend van 13 tot 76 procent van het bruto binnenlands product (BBP). Emran en Stiglitz (2005) hebben reeds aangetoond dat de welvaartswinst van de beschreven gecoördineerde belasting-invoertariefhervorming onder plausibele voorwaarden verandert in een welvaartsverlies indien rekening gehouden wordt met het bestaan van een substantiële informele sector. Hiervoor gebruiken zij echter een statisch model waarin het aanbod van productiefactoren exogeen is. Zoals aangetoond in hoofdstuk 2, beïnvloeden belastingen en tarieven de investeringsbeslissingen van bedrijven. Omdat de formele sector doorgaans kapitaalintensiever is dan de informele sector, is de relatieve verstoring van een invoertarief ten opzichte van die van een consumptiebelasting groter in een dynamisch dan in een statisch model. Het derde hoofdstuk draagt daarom bij aan de academische literatuur door het modelleren van een informele sector en dynamische effecten in een geïntegreerd raamwerk. Door overlappende generaties in de geest van Yaari (1965) en Blanchard (1985) te introduceren, is het model bovendien in staat om *inter*generationele verdelingseffecten van de hervormingen te duiden. De doorgevoerde hervorming bestaat uit het verlagen van het tarief op ingevoerde consumptiegoederen, tezamen met een zodanige verhoging van de consumptiebelasting dat de consumentenprijsindex onveranderd blijft.

De hervorming leidt tot een toename van de overheidsinkomsten en van de in- en uitvoer op lange termijn. De geaggregeerde productie en werkgelegenheid in de formele sector gaan onmiddellijk omlaag, terwijl de productie en werkgelegenheid in de informele sector stijgen. Dit effect wordt sterker gedurende de transitie naar het nieuwe stationaire evenwicht. Startend vanuit een plausibele beginsituatie, leidt de hervorming ondanks het bestaan van een substantiële informele sector tot een welvaartswinst. Dit resultaat is robuust met betrekking tot veranderingen in de grootte van de informele sector. De welvaartswinst die gevonden wordt is ongelijk verdeeld over de generaties: oudere bestaande generaties gaan er meer op vooruit dan jonge en toekomstige generaties.

Conclusie

De dynamische analyse van gecoördineerde belasting-invoertarief hervormingen in hoofdstuk 2 en 3 draagt bij aan de academische literatuur door een belangrijk mechanisme bloot te leggen dat in bestaande analyses genegeerd wordt: de welvaartskosten van invoertarieven als gevolg van hun effect op investeringen en kapitaalaccumulatie. De resultaten tonen aan dat dit mechanisme ervoor zorgt dat het welvaartseffect van de hervormingen hierdoor groter is dan in statische modellen. Bovendien laat de analyse zien dat het welvaartseffect onder plausibele omstandigheden positief blijft, zelfs wanneer rekening wordt gehouden met het bestaan van een omvangrijke informele sector.

Transitie van fossiele brandstoffen naar nieuwe technologieën

Inleiding

Sedert de industriële revolutie vertoont de wereldeconomie een ongekende periode van aanhoudende groei in termen van het inkomen per hoofd. Binnen de economische wetenschap is er veel aandacht besteed aan het identificeren van de determinanten van inkomensgroei en aan het verklaren van de substantiële verschillen tussen landen op dit gebied. Het neoklassieke groeimodel (zie Ramsey, 1928; Solow, 1956; Cass, 1965; Koopmans, 1965) benadrukt de rol van besparingen en de daaruit voortvloeiende accumulatie van kapitaal als groeimotor. Als gevolg van afnemende meeropbrengsten van kapitaal, begint deze groeimotor echter te haperen wanneer de economie zijn stationaire evenwicht nadert. Sterker: zolang de meeropbrengsten van het aggregaat van accumuleerbare productiefactoren afnemend zijn, biedt kapitaalaccumulatie geen uitzicht op aanhoudende verbetering van de levensstandaard, maar is groei van het inkomen per hoofd op lange termijn slechts mogelijk onder invloed van een aanhoudende voortschrijding van de technologie die een continue verhoging van de productiviteit van productiefactoren mogelijk maakt. In het neoklassieke model komt deze technologische vooruitgang als 'manna uit de hemel': technologische ontwikkeling is exogeen. Vervolgstudies op het gebied van economische groei trachten de technologische ontwikkeling endogeen te verklaren aan de hand van positieve externe effecten, leereffecten, en gerichte investeringen in onderzoek en ontwikkeling (R&D) en educatie die de kennisvoorraad in een economie doen toenemen (zie Romer, 1986; Lucas, 1988; Romer, 1990; Aghion en Howitt, 1992; Grossman en Helpman, 1993).

De tot nu toe ten tonele gevoerde economische groeitheorieën abstraheren van de rol van niet-vernieuwbare hulpbronnen, zoals fossiele brandstoffen. Indien niet-vernieuwbare hulpbronnen echter noodzakelijk zijn voor de productie, heeft de eindige voorradigheid van deze hulpbronnen consequenties voor de groeimogelijkheden op lange termijn.[4] Om uitputting van de hulpbron te voorkomen, moet het gebruik ervan op den duur noodzakelijkerwijs afnemen over de tijd. Het belang van niet-vernieuwbare hulpbronnen voor onze energievoorziening—de mondiale energieconsumptie bestaat voor 84 procent uit fossiele brandstoffen (Energy Information Administration, 2012)—doet de vraag rijzen of de aangehaalde aanhoudende groei sinds de industriële revolutie in de toekomst desalniettemin gecontinueerd kan worden. Een duidelijk en ontkennend antwoord op deze vraag werd gegeven door de zogenaamde 'Club van Rome' in hun eerste verslag genaamd 'Grenzen aan de groei' (Meadows et al., 1972). Een van de twee belangwekkendste conclusies van dit rapport is dat "de grenzen aan de groei op deze planeet binnen honderd jaar bereikt zullen worden, indien de huidige groeitendensen in wereldbevolking, industrialisatie, vervuiling, productie van voedsel, en uitputting van hulpbronnen onveranderd aanhoudt. Het meest waarschijnlijke resultaat zal zijn dat de bevolkingsomvang en industriële productiecapaciteit vrij onverwacht en onafwendbaar ineenstorten" (Meadows et al., 1972, p. 29).

Het rapport van de Club van Rome negeert echter twee belangrijke mechanismen die de negatieve effecten van afnemend verbruik van hulpbronnen op de productie kunnen afzwakken: substitutie en technologische ontwikkeling. De eerstgenoemde tekortkoming was de drijfveer voor de ontwikkeling van het zogenaamde Dasgupta-Heal-Solow-Stiglitz (DHSS) model, waarin substitutiemogelijkheden tussen niet-vernieuwbare hulpbronnen en kapitaal worden geïntroduceerd (Dasgupta en Heal, 1974; Solow, 1974a; 1974b; Stiglitz, 1974a; 1974b). Het belangrijkste inzicht van het DHSS model is dat substitutie van kapitaal voor de niet-vernieuwbare hulpbronnen er onder bepaalde stringente voorwaarden voor kan zorgen dat de consumptie niet noodzakelijkerwijs hoeft te dalen op lange termijn (i.e., dankzij substitutiemogelijkheden is de hulpbron niet langer essentieel).[5]

[4]Gebruik makend van de door Dasgupta en Heal (1979) geïntroduceerde terminologie, wordt een niet-vernieuwbare hulpbron 'noodzakelijk' genoemd indien productie nul zou zijn zonder gebruik van een positieve hoeveelheid van deze hulpbron. Een noodzakelijke niet-vernieuwbare hulpbron dient onderscheiden te worden van een 'essentiële': een niet-vernieuwbare hulpbron is louter essentieel indien, vanwege zijn noodzakelijkheid, consumptiemogelijkheden noodzakelijkerwijs nul naderen op lange termijn.

[5]De noodzakelijke voorwaarden zijn: (i) geen constante positieve depreciatievoet van kapitaal, (ii) de substitutie-elasticiteit tussen de niet-vernieuwbare hulpbron en kapitaal moet ten minste 1 zijn, en (iii) de productie-elasticiteit van kapitaal moet groter zijn dan die van de niet-vernieuwbare hulpbron.

Aan deze voorwaarden is in werkelijkheid evenwel vaak niet voldaan, zodat voortdurende technologische ontwikkeling vereist is om niet-afnemende consumptie op lange termijn mogelijk te maken. Behalve de mate van technologische ontwikkeling is de aard ervan ook van belang: technologische ontwikkeling moet ‘hulpbronvermeerderend’ zijn.[6]

Met de inzichten die het DHSS model oplevert, kan de duurzaamheidskwestie dus gereduceerd worden tot de vraag of technologische verandering in werkelijkheid snel genoeg en van de juiste aard is om niet-afnemende consumptie op lange termijn mogelijk te maken.[7] Het DHSS model is niet in staat deze vraag te beantwoorden, omdat het vasthoudt aan de exogene technologische vooruitgang van het neoklassieke groeimodel. Recentere studies gebruiken inzichten uit de endogene groeitheorie om het proces van technologische vooruitgang in hulpbron-afhankelijke economieën expliciet te modelleren (zie Barbier, 1999; Scholz en Ziemes, 1999; Grimaud en Rougé, 2003; Di Maria en Valente, 2008; Pittel en Bretschger, 2010; Bretschger en Smulders, 2012). De resultaten van deze studies wijzen erop dat een duurzame uitkomst mogelijk is indien de groeimotor voldoende kracht heeft, i.e. als de R&D sector productief genoeg is.

De hierboven aangenomen noodzakelijkheid van fossiele brandstoffen voor productie veronderstelt dat er geen goede substituten voor deze natuurlijke hulpbronnen voorhanden zijn. Dit is niet geheel in overeenstemming met de werkelijkheid: de eerste wet van de thermodynamica leert ons weliswaar dat energie inderdaad noodzakelijk is voor productie, maar energie wordt niet louter opgewekt met behulp van fossiele brandstoffen. In 16 procent van de huidige mondiale energiebehoefte wordt voorzien middels alternatieve bronnen zoals nucleaire energie en vernieuwbare energie in de vorm van zonne-energie, windenergie, geothermische energie en biobrandstoffen (Energy Information Administration, 2012). Deze alternatieven voor fossiele brandstoffen worden in de economische literatuur vaak aangeduid met ‘backstop’ (vangnet) technologieën. Dankzij het bestaan van dergelijke technologieën zijn fossiele brandstoffen niet langer noodzakelijk voor productie. Toch worden deze alternatieven nog niet op grote schaal gebruikt, omdat de kosten van het produceren van energie met backstop technologieën doorgaans

[6]‘Hulpbronvermeerderende technologische ontwikkeling’ verhoogt de hoeveelheid energie die verkregen wordt per fysieke eenheid van de hulpbron en kan derhalve worden geïnterpreteerd als een verhoging van de energie-efficiëntie van de hulpbron.

[7]Duurzaamheid is hier gedefinieerd als niet-afnemende consumptiemogelijkheden op lange termijn.

substantieel hoger zijn dan die van het opwekken van energie middels verbranding van fossiele brandstoffen. Als gevolg van technologische ontwikkeling dalen de productiekosten van backstop technologieën echter over de tijd. Bovendien leidt de toenemende schaarste tot stijging van de prijzen van fossiele brandstoffen. In de toekomst lijkt er derhalve een belangrijke rol voor backstop technologieën weggelegd.

Bijdrage en bevindingen

Het bestaan van backstop technologieën leidt tot een fundamentele verandering van de groeiperspectieven op lange termijn, van de ontwikkeling van het gebruik van fossiele brandstoffen over de tijd, en van het effect van hulpbronuitputting op investeringen en de mate en aard van technologische vooruitgang. Het tweede deel van dit proefschrift onderzoekt en beschrijft de effecten van de beschikbaarheid van backstop technologieën op de wereldeconomie. Hoewel het DHSS model alsmede verschillende gerelateerde bijdragen (zie Hoel, 1978; Dasgupta en Stiglitz, 1981; Hung en Quyen, 1993; Van der Ploeg en Withagen, 2012) het bestaan van een backstop technologie of de mogelijkheid tot ontdekking hiervan in ogenschouw nemen, gaan zij uit van exogene technologische vooruitgang, daarmede de interactie tussen technologische ontwikkeling en de transitie van fossiele brandstoffen naar backstop technologieën negerend.

Met het oog hierop introduceren Tsur en Zemel (2003) een R&D sector die gericht is op verbetering van de backstop technologie. Accumulatie van kennis door deze sector verlaagt de productiekosten van de backstop technologie. Chakravorty, Leach, en Moreaux (2012) nemen aan dat deze productiekosten dalen als gevolg van 'learning-by-doing'. Beide studies zijn echter gedaan met behulp van een partieel evenwichtsmodel. De analyse in dit proefschrift vereist echter een algemeen evenwichtsmodel: hoewel de partiële evenwichtsliteratuur een vaste vraagfunctie naar energie postuleert, wordt de vraag naar energie zowel beïnvloed door economische groei en energiebesparende of -verbruikende technologische ontwikkeling, waarmee in een omvattende analyse rekening gehouden moet worden. Bovendien zijn markten voor kapitaal en fossiele brandstoffen intrinsiek verweven, via de relatie tussen de rentevoet en de stijging van de prijs van fossiele brandstoffen. Door een exogeen gedetermineerde rentevoet te veronderstellen, zoals te doen gebruikelijk in partiële evenwichtsmodellen, blijven deze effecten buiten beschouwing.

Er is tot op heden slechts een klein aantal studies verschenen waarin de interactie tussen de endogene groeimotor, de schaarste van niet-vernieuwbare hulpbronnen, en het bestaan van backstop technologieën onderzocht wordt. Tsur en Zemel (2005) ontwikkelen een algemeen evenwichtsmodel waarin R&D de productiekosten van de backstop technologie verlaagt. In hun model is R&D echter alleen mogelijk in de backstop sector, zodat effecten op overige technologische vooruitgang niet geanalyseerd kunnen worden. Tahvonen en Salo (2001) bestuderen de transitie van hulpbronnen naar backstop technologieën in algemeen evenwicht, maar nemen daarbij aan dat technologische vooruitgang voortkomt uit leereffecten in plaats van uit investeringen in R&D. Valente (2011), ten slotte, construeert een algemeen evenwichtsmodel waarin een sociale ingenieur bepaalt of en wanneer er het beste overgeschakeld kan worden van de hulpbron op de backstop technologie. Door te abstraheren van beperkte substitutiemogelijkheden tussen de energie en overige productiefactoren, door een kosteloze backstop technologie aan te nemen, door simultaan gebruik van de hulpbron en de backstop technologie op voorhand uit te sluiten en door zich uitsluitend te richten op het sociale optimum in plaats van op het gedecentraliseerde marktevenwicht, abstraheert hij van elementen uit de werkelijkheid die voor de onderhavige analyse van belang zijn.

Het vierde hoofdstuk van dit proefschrift draagt bij aan de literatuur door de effecten van de beschikbaarheid van een backstop technologie op de mate van technologische vooruitgang en op de ontwikkeling van het verbruik van fossiele brandstoffen over de tijd te duiden in het gedecentraliseerde marktevenwicht van een een analytisch handelbaar, algemeen evenwichtsmodel waarin groei gedreven wordt door R&D gericht op de ontwikkeling van nieuwe intermediaire goederen. Er wordt aangenomen dat er kennis spillovers zijn van de intermediaire sector naar hulpbron sector en de backstop sector. Energie is noodzakelijk voor de productie van het finale goed en kan worden opgewekt met behulp van een niet-vernieuwbare hulpbron of een backstop technologie. In overeenstemming met het empirische bewijs worden energie en intermediaire goederen gemodelleerd als bruto complementaire factoren (zie Koetse, de Groot en Florax, 2008; van der Werf, 2008).[8] Teneinde de belangrijke mechanismen analytisch inzichtelijk te maken, wordt aangenomen dat de backstop technologie in staat is een perfect substituut

[8]Productiefactoren worden bruto complementen genoemd indien de substitutie-elasticiteit tussen de twee kleiner is dan 1.

voor de niet-vernieuwbare hulpbron te produceren.[9]

De belangrijkste resultaten van hoofdstuk 4 zijn, ten eerste, dat de economie verschillende energie-regimes doormaakt: een fossiel regime en een backstop regime. Bovendien is het mogelijk dat er een regime van simultaan gebruik van beide energiebronnen bestaat. Ten tweede resulteert een non-monotoon tijdspad van technologische ontwikkeling, terwijl dit monotoon dalend zou zijn geweest zonder de backstop technologie. In de aanloop naar de overschakeling op de backstop technologie neemt de innovatie toe. Deze toename in investeringen in R&D is een manier om een deel van de welvaart die de hulpbron genereert over te hevelen naar het regime waarin schaarse middelen opgeofferd moeten worden om energie te genereren. Indien het rendement op R&D relatief laag is, vindt deze overheveling deels plaats via het simultaan gebruik regime. Ten derde is technologische vooruitgang gedurende het gehele fossiele regime hoger dan zonder de backstop het geval zou zijn geweest. Ten slotte kent de ontwikkeling van het hulpbrongebruik niet langer noodzakelijkerwijs een dalende fase: afhankelijk van de parameters van het model kan de hulpbronextractie een stijgende ontwikkeling vertonen totdat de voorraad ervan is uitgeput. De vorm van het extractiepad hangt sterk af van de substitutie-elasticiteit tussen de hulpbron en de intermediaire goederen.

Hoofdstuk 5 veralgemeniseert het model door imperfecte substitueerbaarheid tussen de hulpbron en de backstop technologie mogelijk te maken. De substitutie-elasticiteit tussen beide factoren is dus verondersteld eindig en groter dan 1 te zijn. De belangrijkste bevindingen van dit hoofdstuk zijn dat de transitie naar de backstop technologie vrij abrupt plaatsvindt, op een vergelijkbare wijze als in hoofdstuk 4, als de substitutie-elasticiteit hoog genoeg is. Indien de substitutiemogelijkheden beperkter zijn, resulteert echter een geleidelijker overschakeling van de hulpbron op de backstop technologie. Hoe lager de substitutie-elasticiteit tussen beide is, des te langer de periode voortduurt gedurende welke een niet te verwaarlozen hoeveelheid van beide energiebronnen simultaan wordt gebruikt. In overeenstemming met de literatuur over de groene paradox leidt de beschikbaarheid van een backstop technologie tot een toename van hulpbronextractie op korte termijn. Tegelijkertijd wordt ook een 'groen orthodox' effect gevonden: een uitvinding die de substitueerbaarheid tussen de backstop technologie en de hulpbron vergroot, leidt tot een daling van de hulpbronextractie op korte termijn. Ten slotte blijkt dat de lange-termijnuitkomsten van het model niet beïnvloed worden door de

[9] Productiefactoren worden perfecte substituten genoemd indien de substitutie-elasticiteit tussen de twee oneindig groot is.

substitutiemogelijkheden in de energiesector, zolang de substitutie-elasticiteit aldaar groter is dan 1.

Hoofdstuk 6 veralgemeniseert het model in een andere richting: in plaats van het postuleren van kennis spillovers naar de hulpbronsector, wordt nu aangenomen dat er twee verschillende soorten R&D zijn: een soort gericht op arbeidsbesparende technologie en een soort op hulpbronbesparende technologie.[10] In dit hoofdstuk bepalen winstmotieven dus niet alleen de hoeveelheid, maar ook de aard of richting van technologische ontwikkeling. Ter vereenvoudiging wordt in dit hoofdstuk weer teruggevallen op de veronderstelling dat de backstop technologie en de hulpbron perfecte substituten zijn. De belangrijkste resultaten zijn dat de economie twee achtereenvolgende regimes van energieverbruik kan doormaken. De energievoorziening is in het eerste, fossiele regime volledig afhankelijk van de hulpbron. Afhankelijk van de productiviteit van de backstop technologie, kan er op den duur een overschakeling plaatsvinden naar een backstop regime waarin de hulpbron uitgeput is en de backstop technologie in de volledige energiebehoefte voorziet. Als gevolg van de transitie naar de backstop technologie, is de hulpbronbesparende technologische ontwikkeling gedurende het initiële fossiele regime lager dan zonder de backstop technologie het geval zou zijn geweest. De hulpbronbesparing valt zelfs in zijn geheel weg, reeds voordat de backstop technologie daadwerkelijk geïmplementeerd wordt. Vanaf dat moment is de technologische vooruitgang louter arbeidsbesparend.

Vanwege de endogene richting van technologische vooruitgang, vindt de overschakeling op de backstop technologie niet in alle scenario's plaats. Indien de productiviteit van de voorhanden zijnde backstop technologie laag is, blijft de economie voor altijd in het fossiele regime. Voor intermediaire productiviteitswaarden, wordt de implementatie van de backstop technologie een zichzelf-vervullende-profetie: indien investeerders verwachten dat de opwekking van energie voor altijd afhankelijk zal blijven van de niet-vernieuwbare hulpbron, is het verwachte rendement op investeringen in hulpbronbesparende technologieën hoog. Als gevolg hiervan zal de technologische ontwikkeling hulpbronbesparend van aard zijn, waardoor de hulpbron inderdaad relatief goedkoper blijft dan de backstop technologie. Indien, daarentegen, investeerders verwachten dat de backstop technologie in de toekomst concurrerend zal worden, is het minder aantrekkelijk om fors in

[10] Factorbesparende technologische ontwikkeling valt samen met factorvermeerderende technologische ontwikkeling indien de substitutie-elasticiteit tussen de productiefactoren kleiner is dan 1 (zie Acemoglu, 2002).

hulpbronbesparende technologie te investeren. Ten gevolge hiervan zal de hulpbronbesparing bescheiden zijn en uiteindelijk wegvallen, waardoor de backstop technologie inderdaad concurrerend wordt in de toekomst, zodat de overschakeling plaatsvindt.

Conclusie

De algemene evenwichtsanalyse in het tweede deel van dit proefschrift draagt bij aan de academische literatuur door inzicht te bieden in de invloed van de aanwezigheid van backstop technologieën op R&D sectoren en op de sector waarin fossiele brandstoffen gewonnen worden, alsmede in het effect van de R&D sectoren op de energietransitie van fossiele brandstoffen naar backstop technologieën. Het eerste deel van de analyse, hoofdstuk 4, benadrukt het positieve effect van de aanwezigheid van een backstop technologie op de arbeidsbesparende technologische ontwikkeling. Bovendien wordt aangetoond dat de overschakeling van fossiele brandstoffen op een dure backstop technologie gepaard gaat met een toename van investeringen in de vorm van R&D tijdens de jaren voor de overschakeling en eventueel met een regime van simultaan gebruik van beide brandstoffen. Beide effecten worden gedreven door het verlangen van huishoudens om een deel van de welvaart die de hulpbron hen geeft mee te nemen naar het tijdperk waarin het genereren van energie opoffering van schaarse productiemiddelen vereist.

Hoofdstuk 5 controleert de robuustheid van dit resultaat met betrekking tot de substitueerbaarheid van de hulpbron en de backstop technologie. De toename van R&D aan het eind van het fossiele regime blijkt positief af te hangen van de substitutie-elasticiteit tussen de hulpbron en de backstop. Simultaan gebruik vindt nu doorlopend plaats, zodat de rol van het uitsmeren van de hulpbron welvaart hierin moeilijker te onderscheiden is. In het laatste deel van de analyse, hoofdstuk 6, is er ruimte voor zowel arbeidsbesparende als hulpbronbesparende technologische ontwikkeling. De resultaten tonen aan dat tijdens de transitie van fossiele brandstoffen naar de backstop technologie, een toename van de efficiëntie van hulpbrongebruik een tijdelijk fenomeen is: na een initieel regime van zowel hulpbronbesparing als arbeidsbesparing, valt de hulpbronbesparende technologische ontwikkeling weg, reeds voordat de backstop technologie daadwerkelijk concurrerend is. Vanaf dat moment is de economie terug in het model van hoofdstuk 4 en 5. Afhankelijk van de productiviteit van de backstop technologie kan de de uiteindelijke introductie ervan een zichzelf-vervullende-profetie zijn.

Voor wat betreft het verbruik van fossiele brandstoffen, laten de modellen in de hoofdstukken 4, 5 en 6 zien dat de aanwezigheid van een backstop technologie leidt tot een hoger fossiel brandstofverbruik op korte termijn, maar dat een toename van de substitutie-elasticiteit tussen fossiele brandstoffen en de backstop leidt tot een afname van het verbruik van fossiele brandstoffen op korte termijn. Ten slotte blijkt uit de resultaten dat het bestaan van een backstop technologie in combinatie met slechte substitueerbaarheid tussen fossiele brandstoffen en overige productiefactoren kan leiden tot een monotoon stijgend verbruik van fossiele brandstoffen, totdat deze volledig zijn uitgeput.